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"Propelling Efficiency Aids Fighting Efficiency."

A DISCUSSION OF THE DESIGN AND OPERATION OF STEAM JET VACUUM PUMPS.

By J. W. McNULTY, CIVIL MEMBER.

A fluid moving at a high velocity through a space occupied by another fluid, is capable of entraining a portion of the latter, and delivering the whole mass at a pressure greater than that of the entrained fluid. This principle is well known and has been widely used in the past. It has been only in comparatively recent years that the great possibilities for commercial application of apparatus employing this principle have come to be realized, and with this realization, has come an effort on the part of designers and manufacturers to improve the efficiency and widen the application.

This paper is concerned with the application of this principle to apparatus designed to produce and maintain high vacua, and known under the broad name of "Steam Jet Vacuum Pumps." The chief application for this type of apparatus is the removal of air and non-condensible vapors from steam condensers, stills, evaporators, etc.

When steam jet vacuum pumps first came to be generally used, they were crude and inefficient. Like most other power plant auxiliaries, their efficiency as air compressors was not considered a matter of any great importance, for the steam exhausted from them was usually subsequently used in heating the boiler feed water, and thus little or no heat was lost. At that time, the practice of obtaining the steam necessary to heat the feed water by the more efficient method of bleeding the prime mover had not been introduced. With the advent of stage feed heating, such a condition no longer exists, and it is important that each auxiliary give the highest possible efficiency.

Single stage compression for high vacua with steam jet pumps is neither efficient nor practical. For this reason, it is customary to employ two or more stages of jets in series. The high vacuum jet is customarily referred to as the first stage, and the succeeding stages as second, third, etc. For the majority of applications, two stages are sufficient, and this discussion will be limited to this arrangement.

One of the early types of steam jet pumps is shown in Figure 1. The operation is as follows:

The air and other gases are drawn into the pump at A, and are entrained by the jet of steam issuing from first stage nozzle B. The whole mass enters the first stage diffuser C and is compressed to a higher pressure, whence it is expelled into the chamber around the second stage nozzles D. Here the same cycle is again repeated and the gases, together with the steam from both the first and second stage nozzles, are compressed in the second stage diffuser E, and delivered at or slightly above atmospheric pressure.

Perhaps the greatest step in the development of this type pump occurred when a condenser was interposed between the first and second stage jets, the function of which was to condense the steam from the first stage nozzle, leaving only the non-condensi-

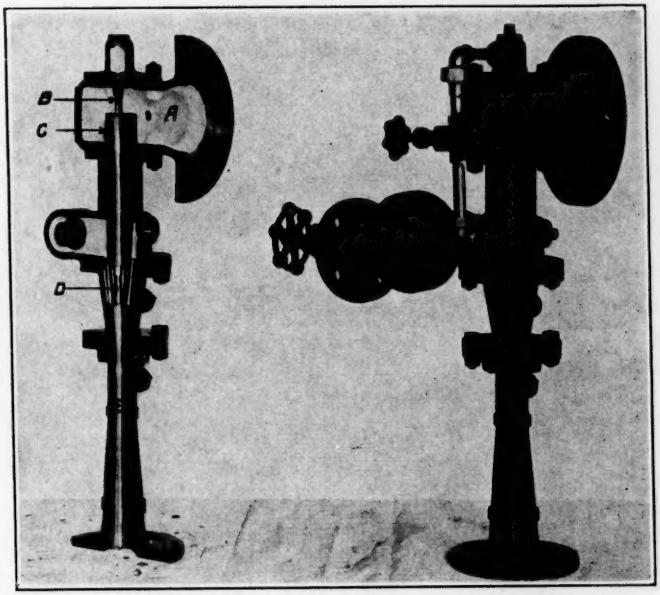


FIG. 1.

ble gases and vapor to pass to the second stage jet, and thus decreasing the duty imposed upon it. This condenser is generally called an intermediate condenser.

Ejectors of this type are shown in Figures 2 and 3; Figure 2 represents a pump having a jet type intermediate condenser; Figure 3 represents a pump having a surface type intermediate condenser. In either case, it is common practice to return the condensate from the intermediate condenser into the main condenser through a line in which is installed a loop of sufficient height to

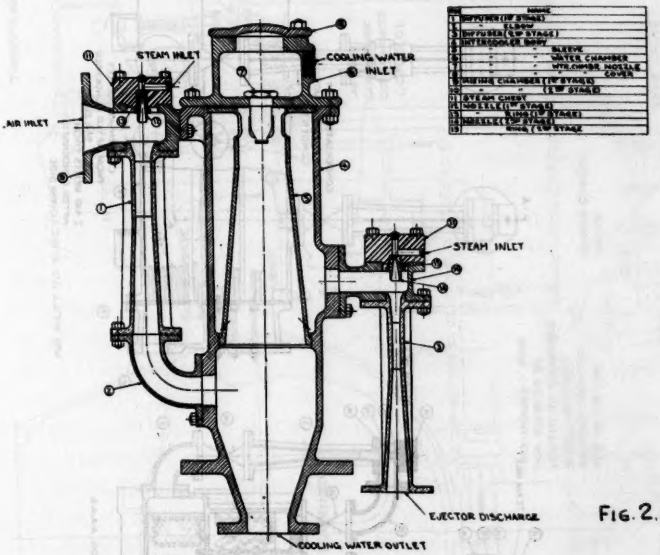


FIG. 2.

form a water seal against the difference in pressure in the main condenser and the intermediate condenser, this difference being normally about 4 inches mercury.

Figure 4 shows the diagrammatic arrangement of an ejector mounted on a surface type intermediate and after condenser serving a surface type main condenser, such as is used to condense the steam from marine engines used for ship propulsion. The use of the main unit condensate through the intermediate condenser

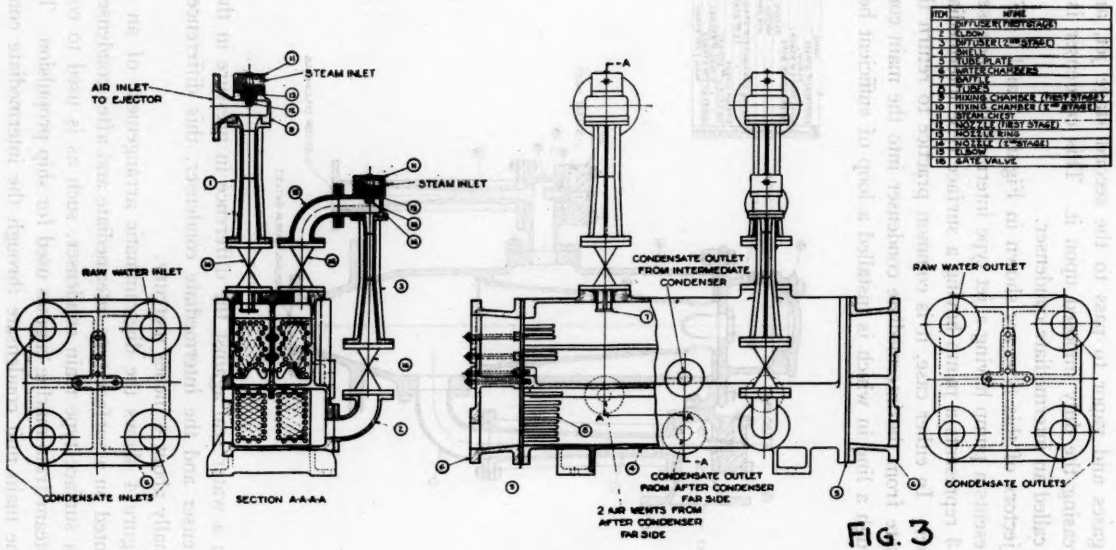

ITEM
NAME
1 DIFFUSER (1ST STAGE)
2 ELBOW
3 DIFFUSER (2ND STAGE)
4 SPLICE
5 TUBE PLATE
6 WATER CHAMBERS
7 BAFFLE
8 TUBES
9 MIXING CHAMBER (1ST STAGE)
10 MIXING CHAMBER (2ND STAGE)
11 STEAM CHEST
12 NOZZLE (1ST STAGE)
13 NOZZLE RING
14 NOZZLE (2ND STAGE)
15 ELBOW
16 GATE VALVE
AIR INLET TO EJECTOR
STEAM INLET
STEAM INLET
RAW WATER INLET
CONDENSATE INLETS
SECTION A-A-A-A
CONDENSATE OUTLET FROM INTERMEDIATE CONDENSER
CONDENSATE OUTLET FROM AFTER CONDENSER FAR SIDE
2 AIR VENTS FROM AFTER CONDENSER FAR SIDE
RAW WATER OUTLET
CONDENSATE OUTLETS

FIG. 3

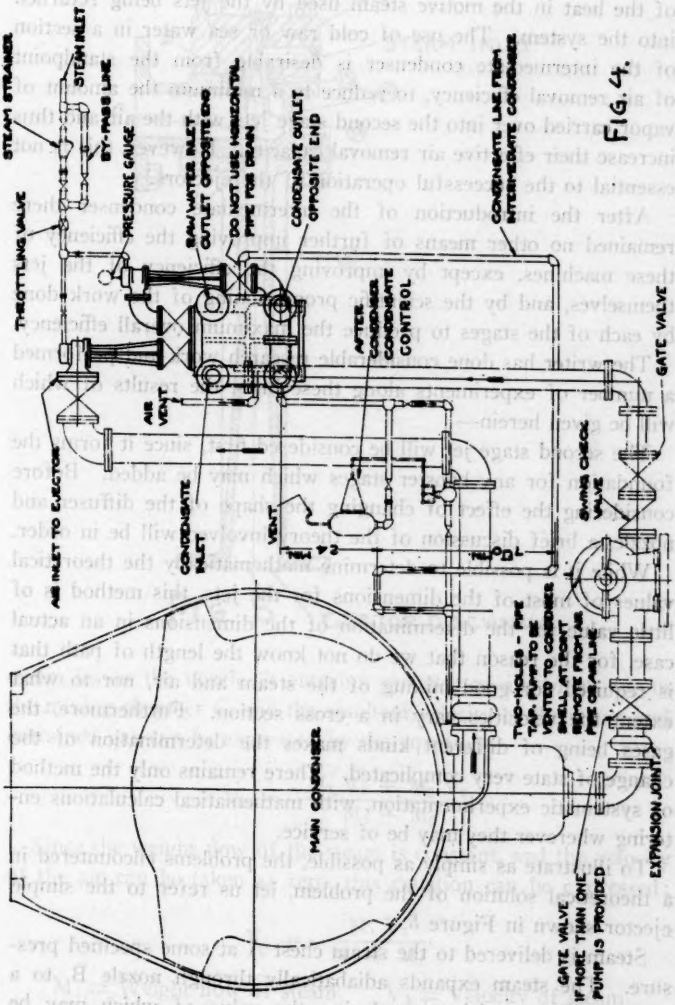

STEAM STRAINER
STEAM INLET
BY-PASS LINE
PRESSURE GAUGE
THROTTLING VALVE
RAW WATER INLET OUTLET OPPOSITE END
DO NOT USE HORIZONTAL PIPE FOR DRAIN
CONDENSATE OUTLET OPPOSITE END
CONDENSATE LINE FROM INTERMEDIATE CONDENSER
AFTER CONDENSER CONDENSATE CONTROL
GATE VALVE
AIR VENT
AIR INLET TO EJECTOR
CONDENSATE INLET
VENT
SWING CHECK VALVE
TWO HOLES - PIPE TAP. PUMP TO BE VENTED TO CONDENSER SHELL AT POINT REMOTE FROM AIR PIPE OR AIR LINE
MAIN CONDENSER
GATE VALVE IF MORE THAN ONE PUMP IS PROVIDED
EXPANSION JOINT

FIG. 4.

and the after condenser, as a condensing medium, results in most of the heat in the motive steam used by the jets being returned into the system. The use of cold raw or sea water in a section of the intermediate condenser is desirable from the standpoint of air removal efficiency, to reduce to a minimum the amount of vapor carried over into the second stage jets with the air and thus increase their effective air removal capacity. However, this is not essential to the successful operation of the ejectors.

After the introduction of the intermediate condenser there remained no other means of further improving the efficiency of these machines, except by improving the efficiency of the jets themselves, and by the scientific proportioning of the work done by each of the stages to produce the maximum overall efficiency.

The writer has done considerable research work and performed a number of experiments along these lines, the results of which will be given herein—

The second stage jet will be considered first, since it forms the foundation for any booster stages which may be added. Before considering the effect of changing the shape of the diffuser and nozzle, a brief discussion of the theory involved will be in order.

While it is possible to determine mathematically the theoretical values of most of the dimensions for the jets, this method is of little value for the determination of the dimensions in an actual case, for the reason that we do not know the length of path that is required for good mixing of the steam and air, nor to what extent the velocities vary in a cross section. Furthermore, the gases being of different kinds makes the determination of the change of state very complicated. There remains only the method of systematic experimentation, with mathematical calculations entering wherever they may be of service.

To illustrate as simply as possible, the problems encountered in a theoretical solution of the problem, let us refer to the simple ejector shown in Figure 5.

Steam is delivered to the steam chest A at some specified pressure. The steam expands adiabatically through nozzle B, to a pressure P_1, acquiring a velocity, the value of which may be found by applying well known laws of thermo-dynamics. As the

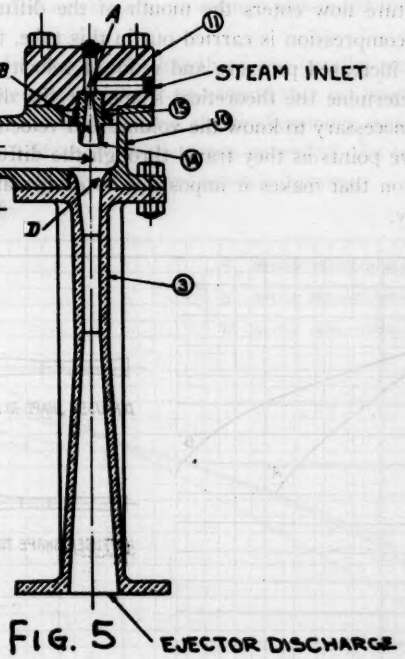


FIG. 5

steam leaves the nozzle, it entrains particles of air which are in the mixing chamber C, and the resultant velocity of the steam and entrained gas can be expressed by the equation:

$$V_R = \frac{M_1 V_1 + M_2 V_2}{M_1 + M_2}$$

Since the weight flow of the steam is constant, and the velocity of the air can be taken as zero, this equation can be expressed:

$$V_R = \frac{M_1 V_1}{M_1 + M_2}$$

M_1 = Weight flow of steam V_1 = Velocity of steam

M_2 = Weight flow of air V_2 = Velocity of air

The mixture now enters the mouth of the diffuser D and the process of compression is carried out in this tube, the gases being expelled at increased pressure and reduced velocity. However in order to determine the theoretical shape for the diffuser tube D, it becomes necessary to know the volume and velocity of the fluids, at successive points as they travel through the diffuser. It is this determination that makes it impossible to design an efficient tube from theory.

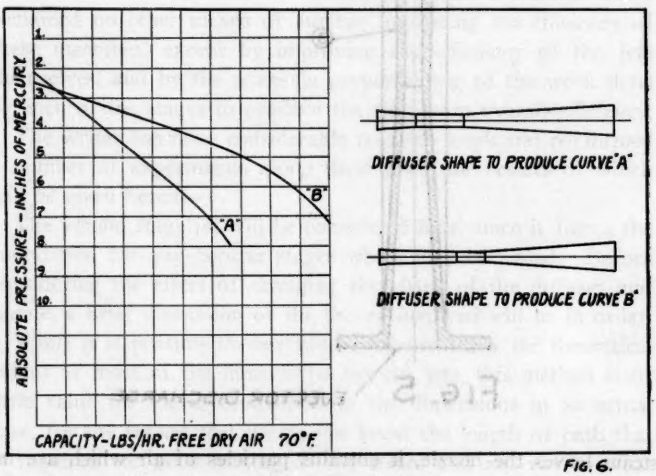


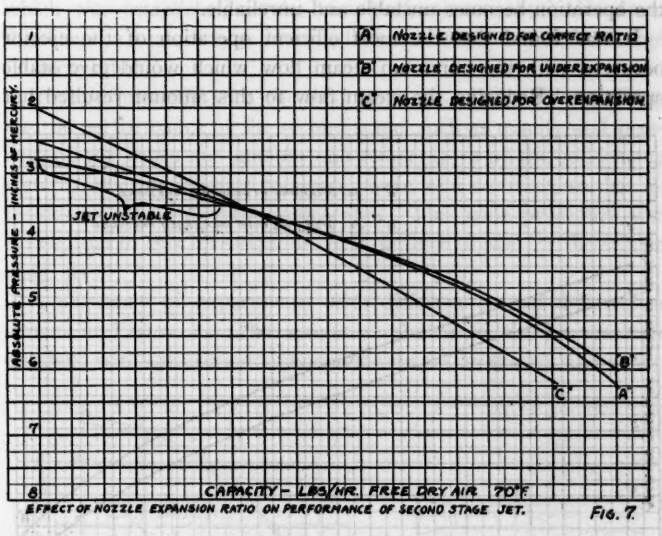
FIG. 6.

The summary of experiments with different shaped diffusers is shown in Figure 6. The results shown by the curves were obtained with diffusers of the general shapes as shown and represent the extreme variations which are possible to use in the design of the diffuser mouth to obtain satisfactory and reliable performance. The curves are plotted on the basis of the same amount of steam in each case. It will be inferred that any intermediate shape will result in producing an intermediate curve. Obviously curve B is to be preferred to curve A.

The effect of changing the diverging taper was investigated, but it was found that this factor has little or no effect on the performance of the ejector. A diffuser was made with this taper not

machined, but used as cast and no change was noted in the relative performance.

The effect of changing the length of the parallel section of the diffuser was investigated, and it was found that for lengths between the limits of 1¼ to 3 diameters, the performance was not appreciably changed. If these limits were exceeded, the performance was found to be slightly impaired in each instance.



EFFECT OF NOZZLE EXPANSION RATIO ON PERFORMANCE OF SECOND STAGE JET. FIG. 7

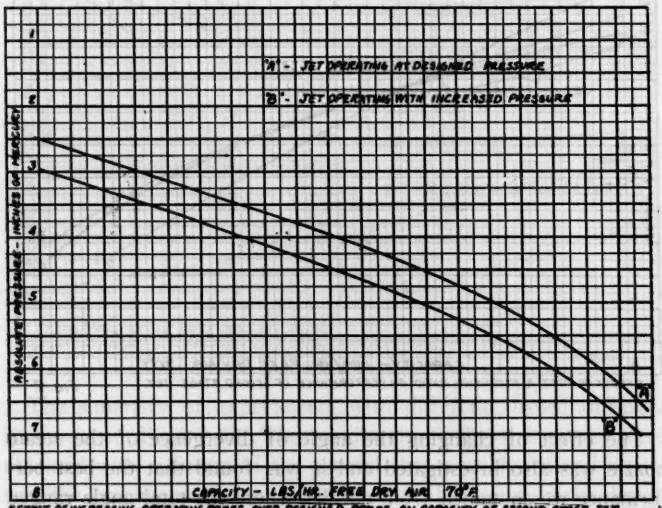
The effect of changing the angle of divergence of the steam nozzle was also investigated and it was found that the best performance was obtained from nozzles where the total angle ranged between 10 degrees and 20 degrees, and within these limits the performance was not appreciably influenced by the angle used.

Nozzles designed for expanding to different pressures within the normal operating range were also tried, and it was found that best all around results were obtained with a nozzle designed for expanding to approximately 3 pounds absolute. If designed for pressures less than this, the capacity of the ejector was reduced at the higher capacity range, and if designed for pressures in

excess of this, the ejector became unstable at low capacities and the performance at the high capacities was not materially improved. This is illustrated in Figure 7.

The effect of changing the distance from the exhaust end of the steam nozzle to the mouth of the diffuser was studied, and it was found that by increasing this distance, the average performance could be improved. The limiting factor in this case is the stable operation of the jet, for if the distance is made too great, the operation becomes unstable and unreliable.

It was found that the most efficient operation of the ejector occurred with the minimum steam flow which would give stable operation. Reducing the steam flow to this amount resulted not



EFFECT OF INCREASING OPERATING PRESS. OVER DESIGNED PRESS. ON CAPACITY OF SECOND STAGE JET. FIG. 8.

only in a saving of the amount of steam used, but in actually increasing the capacity of the jet for removing air. Consequently, the steam nozzle was designed so that with normal operating steam pressure, the steam flow was the minimum that was consistent with stable and reliable operation. The effect of increasing the pressure, and consequently the amount of steam consumed, is illustrated in Figure 8.

Superheat was found to have but little effect on the performance of the pump, provided the weight flow of steam through the nozzles is kept constant. On the other hand, a reduction in the capacity of the pump was noted if steam having a moisture content in excess of approximately 2 per cent was used. The weight flow of steam required to maintain stable operation must also be increased in the latter case.

Using the second stage jet as represented by curve B, Figure 6, which was established as the best performance obtainable from this stage, a surface type intermediate condenser and a first stage jet were added.

In experimenting with the first stage jet, all conditions affecting the performance of the second stage, such as quality and pressure of the steam and amount and temperature of the condensing water to the intermediate condenser were kept constant, so that all results would be directly comparable. The same procedure was carried out in this investigation as is outlined above for the second stage jet.

A summary of experiments with different shaped diffusers is shown in Figure 9. The results as shown by the curves were obtained with diffusers of the general shapes as shown, and repre-

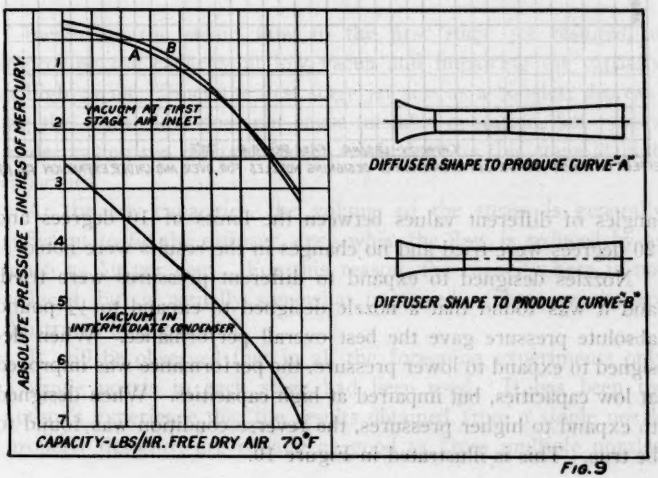
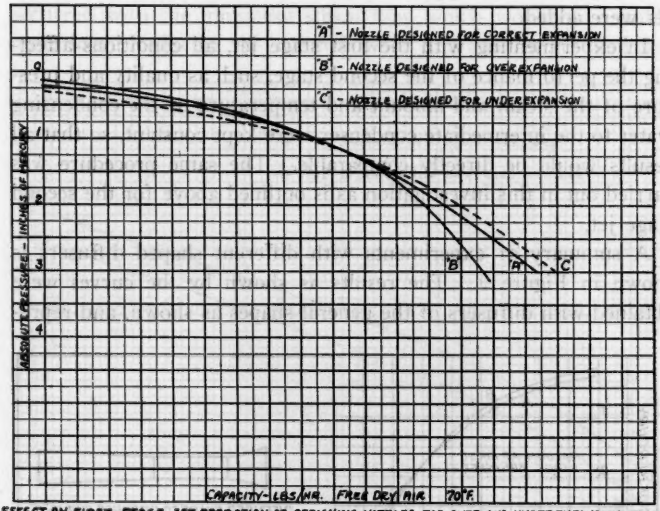


FIG. 9

sent the extreme shapes and angles which it was found, could be used satisfactorily. The curves are plotted on the basis of the same amount of steam in each case. It can be assumed that any intermediate shape will produce an intermediate curve.

As in the case of the second stage jet, changing the angle of the diverging section of the diffuser over a range of several degrees, did not affect the results obtained. Varying the length of the parallel section between the limits of 1¼ and 3 diameters did not produce any noticeable effect. Steam nozzles having diverging



EFFECT ON FIRST-STAGE JET OPERATION OF DESIGNING NOZZLES FOR OVER AND UNDER EXPANSION. Fig 10.

angles of different values between the limits of 10 degrees and 20 degrees were tried and no changes in the results were noted.

Nozzles designed to expand to different pressures were tried, and it was found that a nozzle designed to expand to ½ pound absolute pressure gave the best overall performance. When designed to expand to lower pressure, the performance was improved at low capacities, but impaired at high capacities. When designed to expand to higher pressures, the reverse condition was found to be true. This is illustrated in Figure 10.

The effect of changing the distance from the exhaust end of the steam nozzle to the mouth of the diffuser was studied, and it was found that by increasing the distance, up to the point where the jet became erratic, the capacity would be improved at high vacua, but the capacity at low vacua would be decreased, and vice versa. The proper setting of this nozzle was taken as the position which gave the best average curve. Figure 11 gives a summary of the results obtained with different nozzle settings.

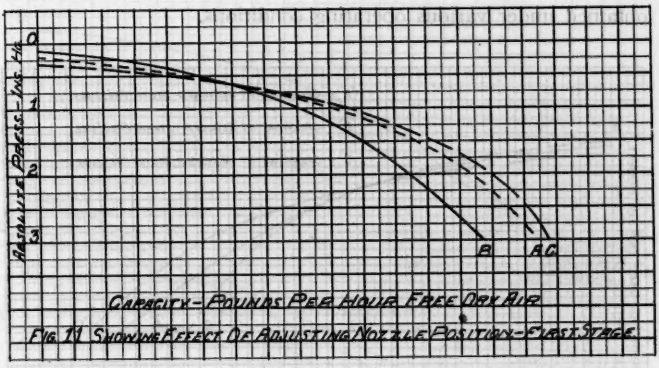


FIG. 11 SHOWING EFFECT OF ADJUSTING NOZZLE POSITION - FIRST STAGE

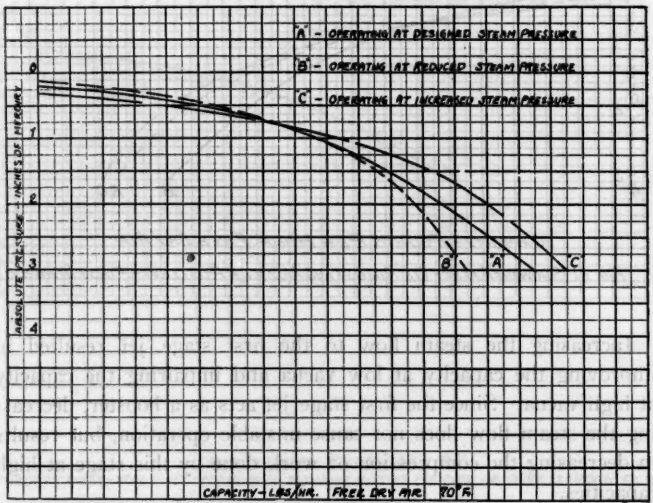
Increasing the steam flow to the first stage jet resulted in improving the capacity at low vacua and impairing the capacity at high vacua. Since the first stage jet acts as a booster, decreasing the steam flow does not cause unstable operation, but results in decreasing the compression or work done by this stage at high capacities.

At the low capacities, the volume of the steam is generally sufficient to fill the diffuser, even when the flow is reduced by as much as 50 per cent. For this reason, the capacity here is not reduced, but is actually somewhat improved. These results are illustrated by Figure 12.

It will be observed that in all the foregoing experiments only a single nozzle in each stage had been used. It has been the author's experience that the results obtained from a single nozzle properly designed are equally as good as from multiple nozzles,

from the standpoint of economy. Aside from this, the mechanical simplicity and freedom from nozzle stoppage, resulting from the use of a single nozzle, make this design more preferable than multiple nozzle design. Experiments on this phase of the design were conducted some years ago and this conclusion was established at that time.

The foregoing text has been devoted to a detailed description of the intricacies of the design of steam jet air pumps. The following pages will be devoted to a presentation of test results obtained under various operating conditions.



EFFECT ON FIRST-STAGE JET OPERATION OF INCREASING AND REDUCING OPERATING STEAM PRESSURE. FIG 12.

After having determined the most efficient shape for each stage jet, a series of tests was run to determine the effect of varying the temperature of the condensing water to the intermediate condenser on the capacity of the jets. The quantity of water was kept constant for all temperatures. The results of these tests, shown in Figure 13, are self-explanatory.

In all the foregoing experiments and tests, the quantity of air was measured by admitting atmospheric air into the jets through

calibrated orifices of the shape shown in Figure 14. This means that the pump was handling atmospheric air, which is practically dry. When the pump is serving a steam condenser, an evaporator or a still, the incoming air is completely saturated and the pump must remove the air in its saturated condition. For this reason, it is necessary to know the effect of the moisture in the air on the capacity of the pump.

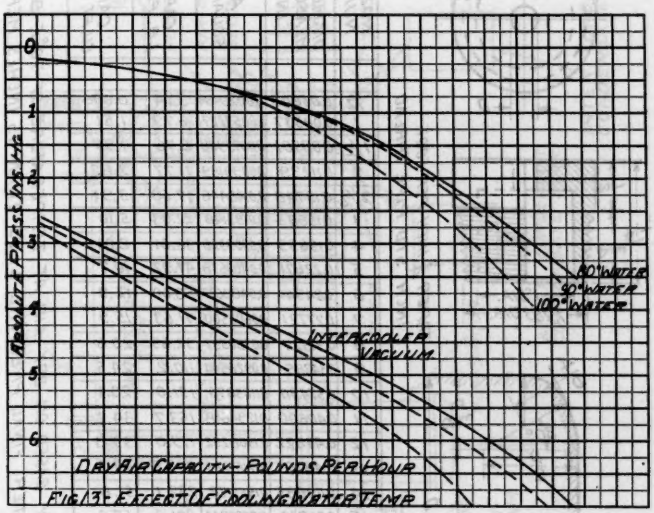
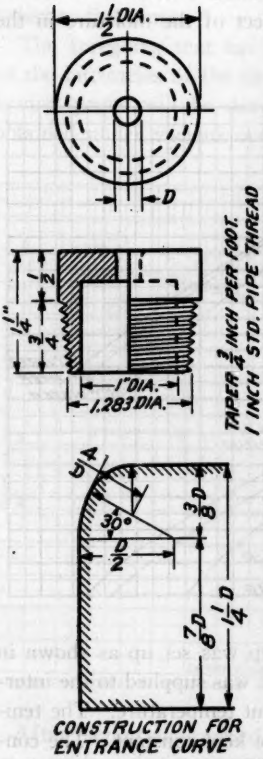


FIG 13 - EFFECT OF COOLING WATER TEMP

For determining this effect, the pump was set up as shown in Figure 15. A constant amount of water was supplied to the intermediate and after condenser at a constant temperature. The temperature and pressure of the steam were kept constant. The condensed steam from the intermediate condenser was drained into a tank where it was emptied at intervals. The condensed steam from the after condenser was drained into the atmosphere. The air was bled into the pump through calibrated orifices similar to the one shown in Figure 14. The pressure in the orifice chamber was recorded to assure that it was always below the critical pressure. The air was conducted from the orifice chamber into a



CONSTRUCTION FOR ENTRANCE CURVE
D = DIAMETER OF ORIFICE

NOZZLE NUMBER	DIAMETER BY MEASUREMENT INCHES	AREA SQUARE INCHES	CAPACITY LB. PER HR.	CAPACITY CU.FT. PER MIN.
1/2	0.05807	0.0026484	3.14	0.698
1	0.08537	0.0057227	6.79	1.51
1 1/2	0.09701	0.0073909	8.76	1.95
2	0.11239	0.0099189	11.77	2.62
2 1/2	0.13748	0.0148446	17.60	3.91
3	0.15683	0.0193148	22.93	5.10
4	0.19653	0.0303320	36.01	8.01
5	0.22671	0.0403638	47.92	10.7
6	0.24944	0.0488677	58.00	12.9
7	0.27721	0.0603500	71.63	15.9
8	0.31527	0.0780597	92.65	20.6
9	0.34385	0.0928544	110.2	24.5
10	0.37490	0.1103876	131.0	29.1
11	0.40600	0.1294618	153.7	34.2
12	0.43822	0.1508252	179.0	39.8
13	0.46755	0.1716829	203.8	45.3
14	0.49895	0.1955178	232.1	51.6
15	0.56823	0.2535844	301.0	67.0
16	0.61981	0.3017120	358.1	79.7
17	0.68735	0.3710504	403.9	89.9
18	0.74950	0.4411974	523.7	116.5
19	0.87595	0.6026126	715.2	159.1
20	0.99885	0.7835763	930.0	206.9

NOTE: CAPACITY BASED ON DRY AIR AT TEMPERATURE OF 70°F. & 29.92 IN. BAROMETER. FINAL PRESSURE LESS THAN 15 INCHES MERCURY

FIG. 14.

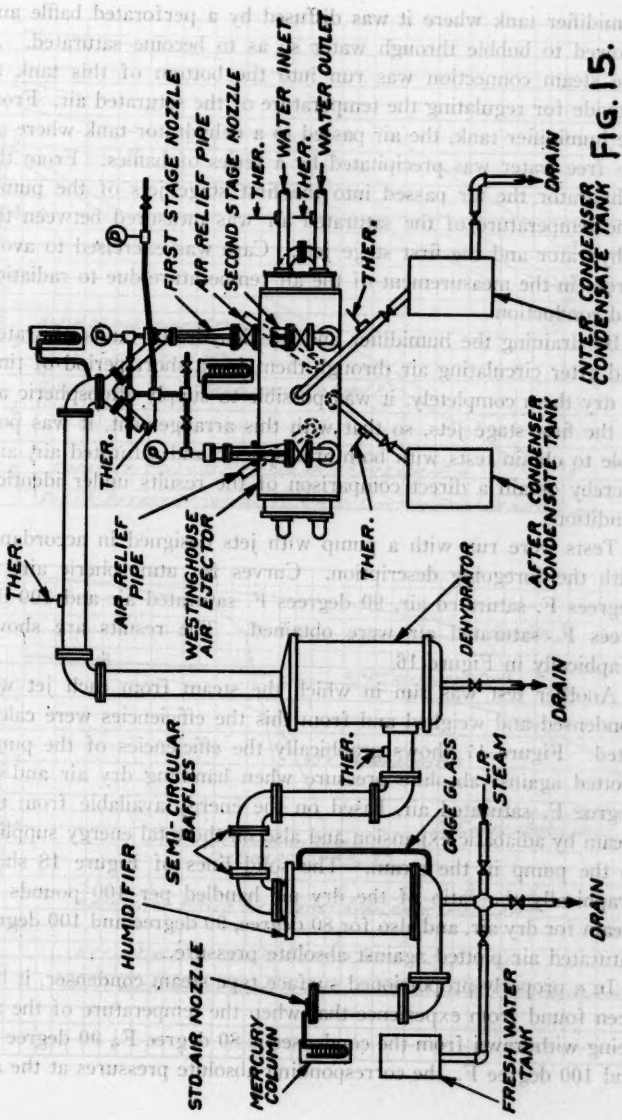

THER.
AIR RELIEF PIPE
WESTINGHOUSE AIR EJECTOR
THER.
FIRST STAGE NOZZLE
AIR RELIEF PIPE
SECOND STAGE NOZZLE
THER.
WATER INLET
THER.
WATER OUTLET
THER.
DRAIN
INTER CONDENSER CONDENSATE TANK
AFTER CONDENSER CONDENSATE TANK
DEHYDRATOR
DRAIN
THER.
L.P. STEAM
GAGE GLASS
DRAIN
SEMI-CIRCULAR BAFFLES
HUMIDIFIER
STD. AIR NOZZLE
MERCURY COLUMN
FRESH WATER TANK

FIG. 15.

humidifier tank where it was diffused by a perforated baffle and allowed to bubble through water so as to become saturated. A live steam connection was run into the bottom of this tank to provide for regulating the temperature of the saturated air. From the humidifier tank, the air passed to a dehydrator tank where all the free water was precipitated by a series of baffles. From the dehydrator the air passed into the first stage jets of the pump. The temperature of the saturated air was measured between the dehydrator and the first stage jets. Care was exercised to avoid errors in the measurement of the air temperature due to radiation and conduction.

By draining the humidifier and the dehydrator tanks of water, and after circulating air through them for a short period of time to dry them completely, it was possible to supply atmospheric air to the first stage jets, so that with this arrangement, it was possible to obtain tests with both atmospheric and saturated air, and thereby obtain a direct comparison of the results under identical conditions.

Tests were run with a pump with jets designed in accordance with the foregoing description. Curves for atmospheric air, 80 degrees F. saturated air, 90 degrees F. saturated air and 100 degrees F. saturated air were obtained. The results are shown graphically in Figure 16.

Another test was run in which the steam from each jet was condensed and weighed and from this the efficiencies were calculated. Figure 17 shows graphically the efficiencies of the pump plotted against absolute pressure when handling dry air and 90 degree F. saturated air, based on the energy available from the steam by adiabatic expansion and also on the total energy supplied to the pump in the steam. The solid lines of Figure 18 show graphically the ratio of the dry air handled per 100 pounds of steam for dry air, and also for 80 degree, 90 degree and 100 degree saturated air plotted against absolute pressure.

In a properly proportioned surface type steam condenser, it has been found from experience that when the temperature of the air being withdrawn from the condenser is 80 degree F., 90 degree F. and 100 degree F., the corresponding absolute pressures at the air

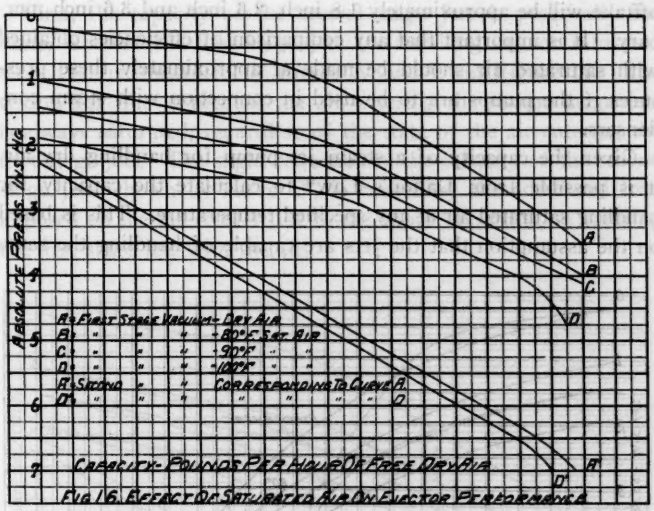

Absolute Press. Ins. Hg.
A = First Stage Vacuum - Dry Air
B = " " " - 80°F Sat. Air
C = " " " - 90°F " "
D = " " " - 100°F " "
A' = Second " " Corresponding To Curve A
D' = " " " " " " D
Capacity - Pounds Per Hour Of Free Dry Air

FIG 16. EFFECT OF SATURATED AIR ON EJECTOR PERFORMANCE

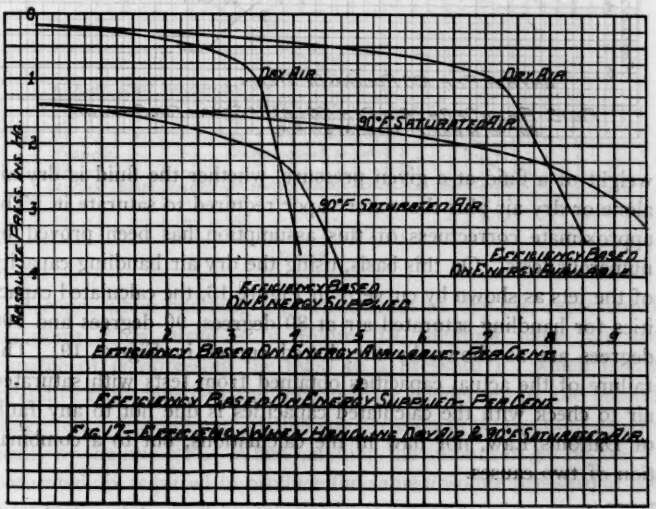

Absolute Press. Ins. Hg.
Dry Air
Dry Air
90°F Saturated Air
90°F Saturated Air
Efficiency Based On Energy Available
Efficiency Based On Energy Supplied
Efficiency Based On Energy Available - Per Cent
Efficiency Based On Energy Supplied - Per Cent

FIG 17 - EFFECT OF VARYING HEAD WHEN HANDLING DRY AIR & 90°F SATURATED AIR.

offtake will be approximately 1.8 inch, 2.6 inch and 3.6 inch mercury. It is important that any comparison of efficiencies obtained with saturated air should be made at approximately these pressures if the pumps are to be used in connection with steam condensers.

Given the capacity of a steam jet pump for handling dry air, it is possible from Dalton's Law* to calculate the capacity for handling saturated air at any specified temperature. This is based on the assumption that the jets are capable of handling the same

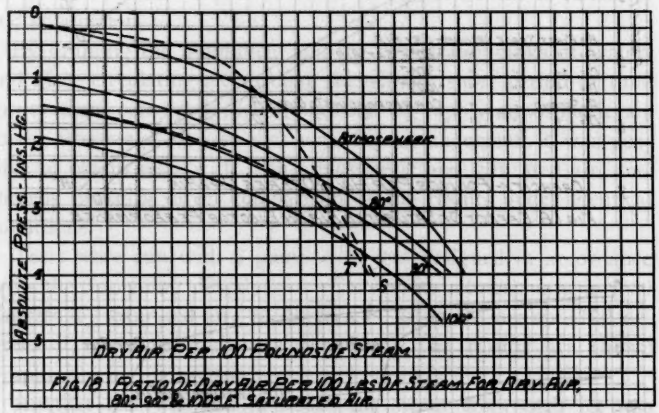


FIG. 19. RATIO OF DRY AIR PER 100 LBS. OF STEAM FOR DRY AIR, 80°, 90° & 100° F. SATURATED AIR.

weight of a fluid at a given pressure, whether the fluid is dry air alone or dry air plus the water vapor required to saturate it. The approximate correctness of this assumption has been proved by numerous tests. On this basis, using the dry air handling capacity of the jets as shown by curve A in Figure 16, the calculated capacities for handling saturated air at 80 degrees, 90 degrees and 100 degrees are as shown by the dotted curves in Figure 19. The failure of the actual capacities obtained from tests with saturated air to check with the calculated capacities is due not to any fault of Dalton's Law, nor flaw in the calculations, but to a combination of two causes.

*Dalton's Law states that the total pressure of a mixture of gases is the sum of the partial pressures of the gases present.

First, the capacity of the second stage jets is practically the same, whether the first stage jets are handling dry or saturated air. This is illustrated by curves A′ and D′ in Figure 16. The reason for this is because the air entering the second stage jets is always saturated, regardless of the state of the air entering the first stage jets. The slight reduction in the capacity of the second stage jets, shown by curve D′, is caused by the additional load imposed on the intercooler due to the vapor or saturation entering the first stage jets with the air.

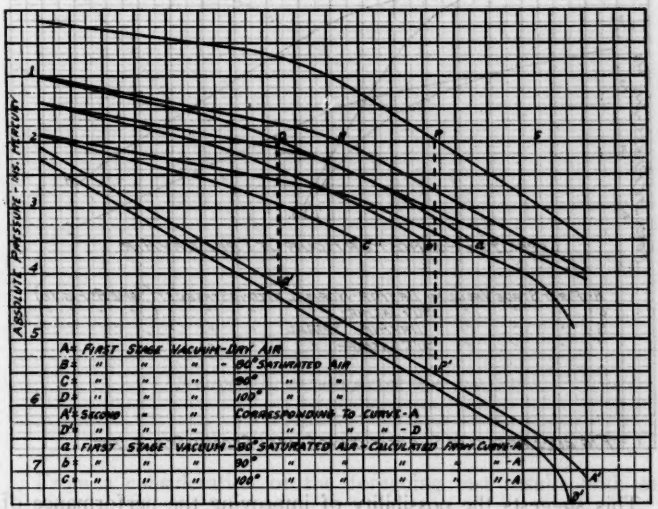

ABSOLUTE PRESSURE - INS. MERCURY
1
2
3
4
5
6
7
A = FIRST STAGE VACUUM - DRY AIR
B = " " " " - 80° SATURATED AIR
C = " " " " 90° " " "
D = " " " " 100° " " "
A′ = SECOND " " CORRESPONDING TO CURVE - A
D′ = " " " " " " - D
a FIRST STAGE VACUUM - 80° SATURATED AIR + CALCULATED VAPOR CURVE - A
b = " " " " 90° " " " " " - A
c = " " " " 100° " " " " " - A
P
P′
Q
A′
D′

FIG-19

Second, when handling a given amount of dry air, represented by point P on curve A of Figure 19, the first stage jets are capable of compressing the mass to a pressure P′, which is the pressure maintained in the intermediate condenser by the second stage jets. The amount of this compression is represented graphically by the line PP′. When handling the amount of 80 degree F. saturated air required to produce the same absolute pressure at the first stage jets, which by calculation is found to be as represented by point Q, the first stage jets have to compress the same total

weight of gas to the pressure Q′, which is less than PP′. By virtue of this reduction in the amount of the compression required of it and the lower pressure into which it exhausts, the first stage jets are capable of handling an increased amount of mixture, containing an amount of dry air as represented by point R, and having a total weight as represented by point S, which is determined by Dalton's Law from point R.

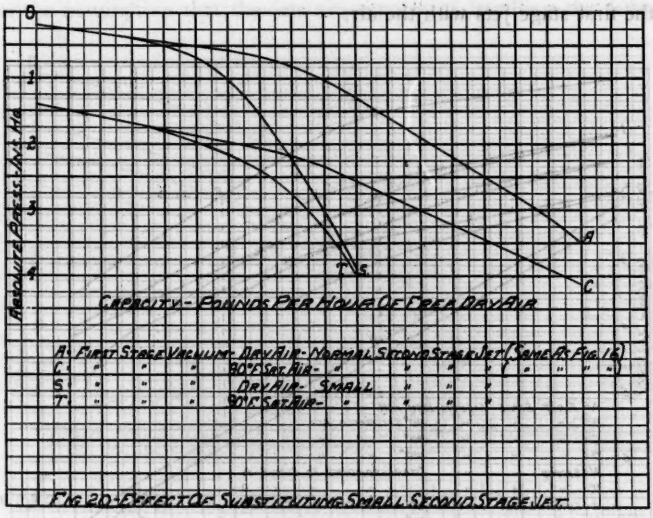

0
1
2
3
4
Absolute Pressure, Inches Hg.
A
C
T
S
Capacity - Pounds Per Hour of Free Dry Air
A- First Stage Vacuum - Dry Air - Normal Second Stage Jet (Same as Fig. 16)
C - " " " - 90° F Sat. Air - " " " " " " " " "
S - " " " - Dry Air - Small " " " " " " " "
T - " " " - 90° F Sat. Air - " " " " " " " "

Fig 20 - Effect of Substituting Small Second Stage Jet

This suggests the possibility of improving the performance of the pump by substituting a smaller second stage jet. This was done, and the results obtained are shown by Figure 20. They are shown in comparison with the results obtained from the pump with the full size second stage. The steam consumption was reduced 28 per cent by substituting the smaller second stage. The comparison in the ratio of air removed per 100 pounds of steam is shown on Figure 18, curves S and T representing the performance of this pump with free dry air and 90 degree saturated air, respectively.

It can be seen that some small improvement may be obtained by this procedure, especially in the free dry air performance. However, since this improvement is obtained at the sacrifice of capacity in the second stage jets, which is so essential for quickly creating an initial vacuum in a system, or where excessive air leakage exists, it is questionable whether this would not be false economy.

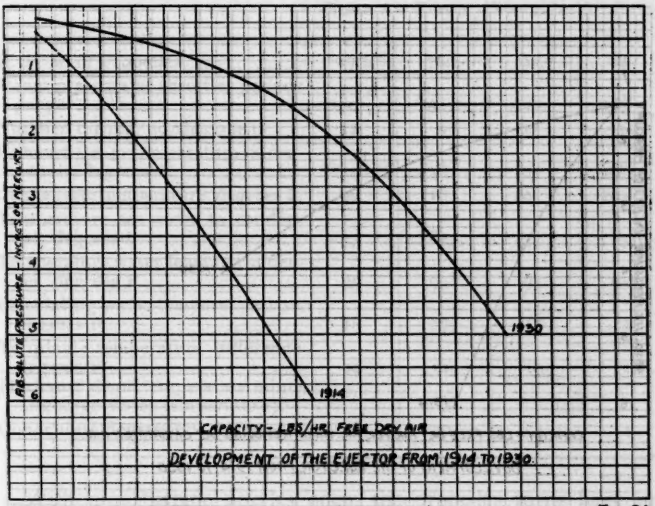


FIG 21.

From a consideration of the foregoing test results with saturated air, it is evident that when applied to evacuate a steam condenser, the steam jet air pump is capable of much better performance than it is usually credited with, based on its capacity for removing saturated air as calculated from atmospheric air handling capacity and Dalton's Law. The only correct method of accurately determining its saturated air handling capacity is from actual tests with saturated air, since it is obvious that the ratio of compression for the two stages will have a direct influence on the ratio of the calculated to the actual saturated air handling capacity. Consideration should be given to these facts when comparison is made between the performance of this and any other type

air pump handling saturated air, as it is the only true basis for comparison.

Obviously the foregoing reasoning does not apply to a multi-stage non-condensing type ejector since any vapor carried over with the air cannot be reduced between the stages, but must be handled by each succeeding stage, in addition to the air and motive steam from the preceding stages.

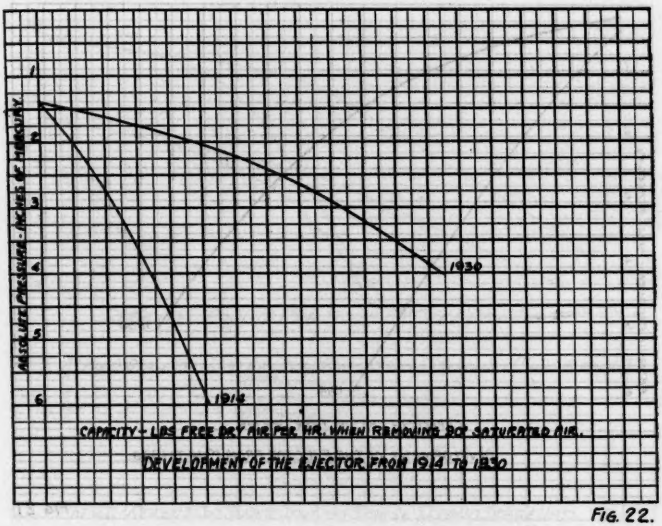


FIG. 22.

The increased efficiency resulting from the improvement in ejector design from 1914 to the present time is illustrated in Figure 21. This comparison is made on the free dry air removal capacity basis. The influence of modern high vacuum turbines on ejector design is shown by the marked improvement in capacity at pressures below 2 inches absolute.

The superiority of the modern ejector is still more apparent when comparison is made on the basis of removing moisture saturated air, such as is removed from a steam condenser. This is shown in Figure 22.

A concrete example of the improvement obtained on a modern merchant ship by the installation of a steam jet vacuum pump is

shown in the tabulation below. This ship was originally equipped with the conventional beam type reciprocating wet vacuum pump, and when the steam jet pump was installed the original pump was retained, so that the data given is a direct comparison of the effectiveness of the two pumps.

	Operating with Beam Air Pump		Operating with Steam Jet Air Pump	
R. P. M. of Propeller	87.6	76.8	90.7	84
Steam pressure at throttle, pounds gauge	190	194	190	195
Number turbine nozzles open	12	9	12	9
Exhaust steam temperature in condenser, degrees F	124	138	105	106
Condensate temperature, degrees F.	96	118	102	102
Temperature sea water to condenser, degrees F	77	82	77	83
Temperature water leaving condenser, degrees F	95	99	95	95
Circulating water temperature rise, degrees F	18	17	18	12
Terminal temperature difference, degrees F (Exhaust steam temperature minus discharge water temperature).	29	39	10	11
Condensate depression, degrees F.	28	20	3	4

With nine turbine nozzles open, the propeller turns have increased 9.4 per cent, which represents an increase of 31 per cent in the power output of the turbine with the same amount of steam consumed. Some of this improvement is due to the increased amount of cooling water, but for the most part it is due to the greater air handling efficiency of the jets.

With twelve nozzles open, the improvement is not as great, due presumably to the larger volume of steam which must pass through the turbine blading, which results in lowering the blade efficiency.

THE TREND IN NAVAL ENGINEERING.
STORAGE BATTERIES.
NICKEL-IRON-ALKALINE TYPE VS. LEAD-ACID TYPES.

By C. Huey, Civil Member.*

Of late years the nickel-iron-alkaline storage battery has been practically superseded in the Navy by the lead-acid types of batteries. Although the nickel-iron-alkaline battery has many excellent features, the causes of the trend to the lead acid types of batteries are analyzed as follows:

The use of alkaline batteries for submarine propulsion was first proposed in 1910. Portable batteries of this type had been used for a number of years with varying degrees of success. In 1914, three sample submarine cells were submitted to the Navy and were tested in comparison with samples of two different makes of lead-acid batteries. After 500 cycles of charge and discharge, these batteries gave rated capacity and were in good condition. Based on these results, installation was made of a complete alkaline battery for propelling the U. S. S. Submarine E-2.

As a result of the experience obtained on the E-2 installation and many special tests made after removal of the alkaline batteries from the E-2, together with results and experiences with portable batteries for general purpose on shipboard, the following advantages and disadvantages are summarized:

ADVANTAGES OF ALKALINE BATTERY.

(a) *Higher Capacity per Unit of Weight.* For equal Kw-hour capacities, the alkaline battery weighs approximately 15 per cent less than the average lead battery. However, it occupies about

Note by Editor. These are the second and third articles on "The Trend in Naval Engineering." The first appeared in the February, 1931 Journal.

*Material Engineer, U. S. Navy Yard, New York, N. Y.

the same unit of space at the same Kw-hour output at the 6 hour discharge rate.

(b) *Stronger Mechanically.* The alkaline cell is stronger mechanically and capable of withstanding more abuse, such as shock and rough treatment, without injury.

(c) *Stronger Electro-chemically.* The alkaline cell is capable of withstanding more abuse, such as over-charging, under-charging, short-circuiting, over-discharging, and allowing to stand idle for long periods when discharged.

(d) *Safer When Submerged in Sea Water.* The alkaline cell can be submerged in sea water without liberation of chlorine. The lead cell liberates chlorine as a result of electrolysis between lead-covered electrodes.

(e) *Non-corrosive Electrolyte.* Potassium hydroxide is non-corrosive to metals and will not injure metal fittings or adjacent metal parts. However, it is very corrosive to animal or vegetable material.

DISADVANTAGES OF ALKALINE CELL.

(a) *Higher First Cost.* The first cost of an alkaline battery is from 25 to 75 per cent higher than equivalent lead batteries.

(b) *Shorter Life.* Contrary to general belief, the life of alkaline cells has been found to be shorter than that obtained with the best types of lead cells. Comparative test on submarine cells showed a life of from 60 to 75 per cent of that obtained on the so-called lead cells. *Portable* alkaline batteries, however, show a considerably longer life than any lead battery except the so-called "iron-clad" type.

(c) *Lower Efficiency.* The kilowatt hour efficiency averages 60 per cent compared with 75 per cent for lead cells.

(d) *Less Suitable for High-rate Discharges.* Alkaline cells, because of their high internal resistance, are much less suitable for high-rate discharge than lead cells. The fact that an alkaline cell can be short-circuited without serious injury is occasioned by the comparatively low current obtained on short-circuit.

(e) *Less Suitable for Low Temperature Operation.* An alkaline cell has a certain critical temperature below which very little

capacity can be obtained. This critical temperature is about 41 degrees F. at the one hour rate.

(f) *Possibility of Gassing on Discharge.* If one cell of any battery, on discharge, has a lower capacity than the others, and becomes discharged more quickly than the others, this cell will reverse due to the continued passage of line current in the discharge direction. Reversal of a lead-acid cell causes it to reverse its chemical formation to practically full reversed potential but does no harm other than injury to the reversed plates. Reversal of an *alkaline* cell practically does not build up reversed chemically and causes no injury to the plates, but all of the current which passes through the cell is utilized to decompose the electrolyte. Large quantities of oxygen and hydrogen gases are liberated by the decomposition of the water constituent of the electrolyte. These gases, in combination, are highly explosive in wide proportions.

(g) *Larger Voltage Variation on Discharge.* The voltage variation of an alkaline cell on a normal discharge is 1.4 volts start to 0.9 volts finish or 35.7 per cent reduction. The variation of a lead cell on similar discharge is 2.04 volts start to 1.7 volts finish, or 16.6 per cent reduction. The large voltage variation of the alkaline cell is a disadvantage as a source of power supply.

(h) *Higher Initial Open Circuit Capacity Loss.* The ultimate loss of charge of alkaline and lead cells is about the same over a long period of standing on open circuit. The self-discharge of a lead cell is approximately uniform over this standing period. The self-discharge of an alkaline cell is greatest during the first 24 hours, as more than one-half of the total loss of charge over a month occurs during this first 24 hours. This constitutes a disadvantage for many classes of service, particularly submarine propulsion, on account of the loss in immediate reserve power.

(i) In addition to the disadvantages enumerated above, there are others of less importance. When alkaline cells are purchased, the Government loses the advantage of competitive bidding because there is only one manufacturer in this country. The contention may be advanced that the alkaline cell manufacturer has to compete against all of the lead cell manufacturers. This would only be true were it possible to use either alkaline or lead cells for any

given installation. On a submarine installation, for example, the design of the entire ship is affected by the type of battery to be installed. This is for the reason that the two batteries have different charge and discharge voltage characteristics. They also have different weights and occupy different spacing. Thus, it is necessary to decide before-hand which type of battery will be used. If it is decided to specify an alkaline battery, the Government thus loses the advantage of competitive bidding. This will also apply in many cases, to portable battery applications.

(j) When two entirely different types of battery are in use, it is necessary to issue operating instructions for each type, and to carry two kinds of electrolyte in stock. This leads to confusion among the operating personnel.

Thus, so far as the Navy is concerned, the disadvantages of alkaline batteries outweigh the advantages, and the trend is at present entirely toward the lead-acid type of storage battery for all purposes.

DIRECT CURRENT MOTOR AND GENERATOR COMMUTATORS—FLUSH INSULATIONS VERSUS UNDERCUT.

By C. Huey, Civil Member.*

Electric power for all regularly equipped auxiliaries in Naval service at present, is generated by direct current generators, and all electric power driven equipment or appliances, excluding the main drive alternating current electric propulsion and special instances, are driven by direct current motors. The exclusion of *alternating* current motors for general purposes in the Navy, is based on the greater flexibility of *direct* current motors as regards starting torque and control of speed, although alternating current motors in their present state of development are entirely suitable for many applications such as for hull ventilation, galley and laundry appliances, motor generator sets, circulating and pres-

* Material Engineer, U. S. Navy Yard, New York, N. Y.

sure pumps, or any purpose where a constant running speed, at all loads, is the prime factor.

For such classes of duty as anchor hoists, boat cranes, steering gears, turret turning, gun elevation, etc., where controlled variable speed, large starting torque and electric braking is required, *alternating* current motors, as so far developed, do not furnish the same flexible performance and control as do heavily compounded *direct* current motors.

Alternating current motors, especially the squirrel cage induction type, due to the absence of commutators, brushes and revolving windings, are free from many of the inherent causes of failure of direct current motors, but for economical reasons, until alternating current motors are entirely applicable for *all* purposes in Naval ships, the direct current commutating motors with the associated direct current commutating generators, constitute the electric power equipment for all auxiliaries.

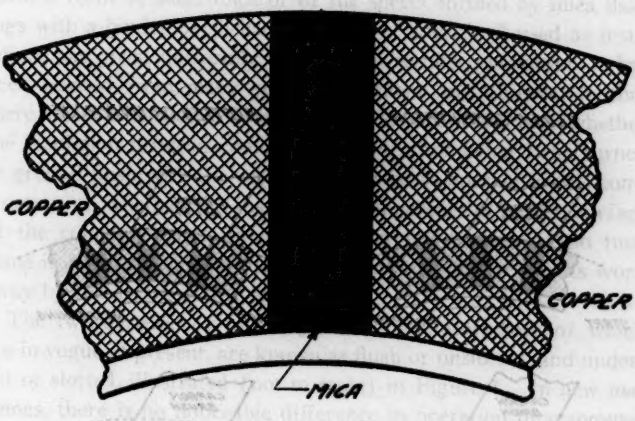
The foregoing explains the reasons for the prevalence of *direct* current motors and generators in Naval service. The indications are, that it will persist for an indefinite time. It behooves therefore, that every effort be made to increase the reliability and reduce the causes of failure of *direct* current motors and generators.

One of the principal causes of failure and poor performance, is indicated by the subject matter—the commutator. It is unexplainable that at this late date of electrical development, that any part of the direct current motor or generator should require modification of design or explanation of operating characteristic which would result in a marked change in service performance.

The commutator, as we know, is built up of hard-rolled or drop forged copper segments, which are insulated from each other by mica or pressed mica plate, the assembly being insulated from, and secured by, cast iron or steel V—ring clamps. By virtue of the proper form of copper, clamp rings and insulation, and by seasoning and tightening at heats higher than operating temperatures, the commutators of Navy machines for the past ten or fifteen years may be said to have given excellent results so far as affected by design, materials and workmanship—with one exception.

This exception is concerned with the insulation between the segments of the commutator copper bars. The quality of the

FLUSH COMMUTATOR



SLOTTED OR UNDERCUT.

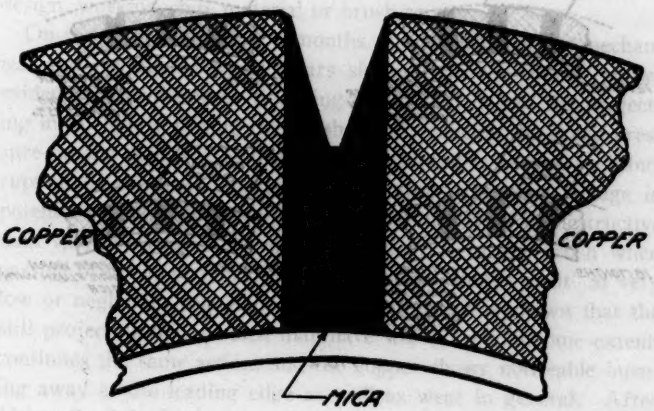


FIG. 1.

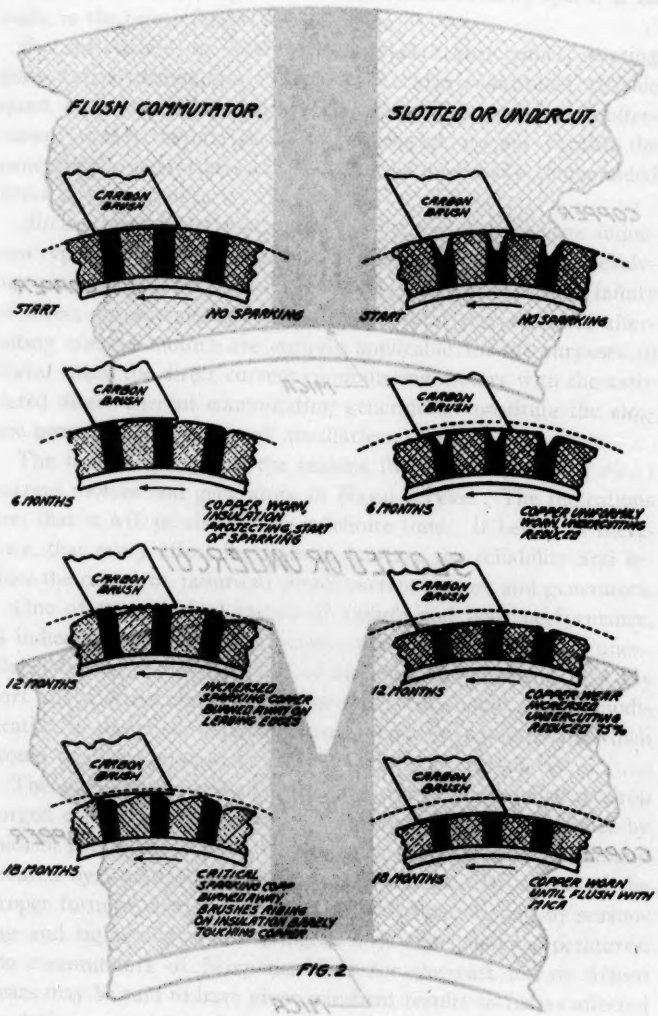

FLUSH COMMUTATOR.
SLOTTED OR UNDERCUT.
CARBON BRUSH
START
NO SPARKING
6 MONTHS
COPPER WORN, INSULATION PROTECTING, START OF SPARKING
COPPER UNIFORMLY WORN, UNDERCUTTING REDUCED
12 MONTHS
INCREASED SPARKING COPPER BURNED AWAY ON LEADING EDGES
COPPER WEAR INCREASED, UNDERCUTTING REDUCED 75%
18 MONTHS
CRITICAL SPARKING COPPER BURNED AWAY, BRUSHES RIDING ON INSULATION & BARELY TOUCHING COPPER
COPPER WORN UNTIL FLUSH WITH MICA

FIG. 2

natural form of sheet mica or of the sheets formed by mica flakings with a binder of shellac, known as "Micanite," used as insulation, has given uniformly satisfactory results. However, it has been learned from many years experiment and observation that there exists a marked difference in service operation as to whether the insulation between commutator bars, after being lathe turned or ground flush with the copper, is allowed to operate in this combination or whether the insulation is undercut below the surface of the copper, so that the current carrying brushes at no time come in contact with the insulation even after the copper is worn away by the action of the brushes.

The two systems of finishing the commutator, both of which are in vogue at present, are known as flush or unslotted, and undercut or slotted, illustrated (not to scale) in Figure 1. In new machines, there is no noticeable difference in operation or commutation between either system. However, the real difference is apparent after a few months of operation. The progressive change to be expected in a commutator of a motor generator from start to 18 months of service is shown for the two systems in Figure 2 (not to scale). As hypothetical examples, it is assumed that the machines are such that there exists no inherent sparking due to design, workmanship, material or brush setting.

On the *flush* type, after 6 months, the mica which for mechanical and electrical reasons wears slower than the copper, shows evidence of projecting. Sparking is initiated due to the projecting mica slightly raising the brushes and reducing the brush pressure on the copper. Sparking thus produced is caused by interruption of the main line current and approaches line voltage in potential difference. This form of sparking is more destructive than sparking caused by commutation action of the brush when passing over two or more bars which are in "short circuit" at very low or negligible voltage. After 12 months, it is shown that the still projecting mica, which may have worn down to some extent, continues the same action, and the copper shows noticeable burning away at the leading edge as well as wear in general. After 18 months, it is shown that the continuous sparking under the influence of projecting mica, has caused excessive erosion over a

greater width of the bars. The motor at this stage would show excessive sparking, blackening of commutator bars, ring fire, and falling off in speed. On a generator, it would show fluctuating and lowering voltage.

On the slotted type, after 6 months, the copper would show only a moderate but uniform amount of wear. The mica, being undercut, and not in contact with the brushes, bears no part in the condition of the commutator. There exists no mechanical reason for sparking, or burning of the copper. After 12 months, it is shown that the copper still continues to wear normally and uniformly, without burning. The amount of undercutting of the mica would be reduced equal to the amount by which the copper is worn. After 18 months, it is shown that the copper has worn down uniformly without burning, until it is flush with the mica. At this time the undercutting should be renewed for further continued service.

From the foregoing it would appear that the operating conditions are overwhelmingly in favor of the undercut commutators and that, when the comparative operation of the two systems was generally known, the manufacturers of the machines and the purchasers in general, would quickly come to a decision to adopt the slotted or undercut commutators as standard practice.

However, the trade has shown considerable resistance to adopting undercut commutators, which may be explained on the basis of, first, the added cost of undercutting. On small, low-cost armatures, it is somewhat a tedious operation, and requires appreciable time to accomplish a satisfactory job. On the large armatures, with many commutator bars of considerable length the operation is very slow and the cost of the same is perhaps considered to be an unnecessary expense considering, from the manufacturer's standpoint, that there exists no appreciable difference in operation during the acceptance test of the machine as to whether the commutator is undercut or not. Second, the manufacturers of carbon brushes have long influenced the machine manufacturers to believe that carbon brushes with a certain amount of abrasive as a constituent, satisfactorily keeps the mica of flush commutators worn down flush with the copper. This is true to a certain extent.

However, it has always been a "cut and try" method as to how much abrasive should exist in the brushes for the varying hardness existing in copper and mica. Laboratory tests have failed to support the manufacturers' contention that abrasive constituents were a controlled addition to the carbon. Tests rather indicate that the so-called abrasive consists of a varying amount of iron oxide existing as an impurity.

The general results of using abrasive brushes has been in severe mechanical wear of the copper, excessive heat producing friction, abnormal wear of the brushes, and the presence of considerable copper and carbon dust on the windings and insulated parts.

On the other hand, for undercut commutators, it is practical to fabricate a carbon brush with inappreciable abrasive impurities. This naturally greatly reduces the number of *grades* of carbon and permits the requirements to cover only the essential commutation contact drop, current carrying capacity, and minimum friction and wear, at operating speeds. The prevailing idea that the grooves in the insulation of undercut commutators eventually fill up with dust-laden oil from the bearings, or carbon and copper dust, and cause short circuits between commutator bars, has not been substantiated in modern machines. Improvement in oil bearings, and the increased use of grease lubricated ball bearings, has reduced the oil troubles to negligible amount. Centrifugal force and windage serves, with unlubricated brushes, to keep the grooves in the insulation clear of any copper and carbon dust which exists according to the amount of wear. With proper undercutting, and infrequent clearing of the grooves, experience has shown very satisfactory results on all types of commutators regardless of commutator surface speeds.

The trend, so far as concerns the U. S. Navy, is for *undercut* commutators. This is evidenced by the most recent generator and motor specifications which requires that all generators, and motors of one horsepower and larger shall have the mica insulation between bars undercut not to exceed 3/64 inch in depth. This is further evidenced by recent general instructions to undercut, as opportunity offers, all flush commutators now in service.

TREND IN DIESEL FRAMING AND THE FUNCTION OF THE TIE ROD.

By Lieutenant John O. Huse, U. S. Navy, Member.

This paper purposes to present to the reader, in Part I, the various steps in the development of the Diesel frame design, the materials employed, and the trend in framing; and, in Part II, the action of the tie rod on the frame.

Part I.

The European Trend in Lightweight Four-Cycle Diesel Engine Framing.

The trend toward higher speed, lighter weight, and less space in modern Diesel design is caused primarily by the rigid space and weight limitations of the submarine, locomotive, yacht, automotive, and aircraft power plant.

This trend has expressed itself in many forms of which the following are a few:

1. Increase in speed.
2. Simplification of design of (a) stationary and (b) moving parts.
3. Adoption of solid injection.
4. Improvement in materials.
5. Use of two-cycle and double-acting design.
6. Increase in mean effective pressure.

This article will limit discussion to the framing of the high-speed, lightweight, four-cycle Diesel engine from 25 H. P. to 200 H. P. per cylinder. In other words the subject matter is 2 (a) above.

A table has been prepared giving the framing design of thirty engines of this type constructed by fifteen European manufacturers. This table shows clearly the trend in framing design.

Since many of these designs are confidential, and in the experimental stage, it will be impossible to refer to manufacturers or publish details of particular types.

No engine weight on this table is over thirty pounds per horsepower. All types have been developed since the World War.

To illustrate the important part played by the framing in the saving of weight, it is only necessary to point out that the box framing castings of a wartime 1200 H. P. 6-cylinder engine weighed as follows:

Main cylinders without studs or liners (cast steel)	7647 pounds
Cylinder liners (cast iron)	4070 pounds
Crankcase without bearing caps (cast steel)	7394 pounds
Cylinder heads (cast steel)	3762 pounds
Total	22,873 pounds.

The weight of the complete engine was 54,978 pounds. The castings of the frame alone weighed 41.6 per cent of complete engine.

Therefore, since the frame castings play such a large part in engine weight, it may be expected that the lightening of the frame is an important factor in the trend toward light-weight engines.

VARIOUS TYPES OF FRAMING.

Framing design may be divided roughly into the following general types:

1. Open "A" frame with separate columns.
2. Closed box frame without tension members.
   (a) Cylinders separately fitted.
   (b) Cylinders integral with frame.
3. Closed box frame with tension members.
   (a) Cylinders separately fitted—partial tie rod.
   (b) Cylinders integral with frame—full tie rod.
4. Closed "A" frame with integral columns and tension members.
   (a) Cylinder entablature forms upper girder.
   (b) Bolted up or enbloc cylinder heads form upper girder.

5. Box frame or closed "A" frame with suspended bearings and no bedplate.

6. Eccentric framing.

(a) Radial Type.

(b) "Vee" Type.

(c) Barrel Type.

(d) Miscellaneous.

1. *Open "A" frame with separate columns.* (See Figure 1.)

This was adopted for early Diesel engines from steam engine practice. The design was abandoned when forced feed lubrication was adopted by Diesel designers.

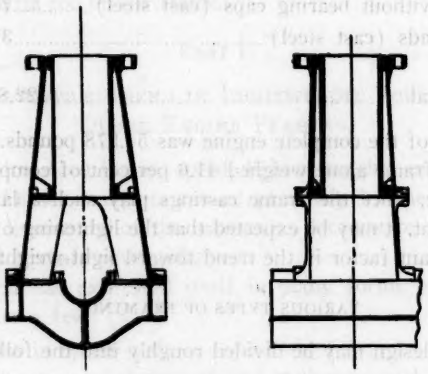


FIG. 1

2. *The closed box frame without tension members.*

(a) Cylinders separately fitted (see Figure 2) gives poor beam strength and very bad transmission of tensile stresses. It is still used in heavy, cheap engines of low rating and slow speed. High-speed, light-weight designs have abandoned this construction except in very small sizes below 25 horsepower per cylinder.

(b) The closed box frame with cylinders integral with frame (cast enbloc or bolted up) (see Figure 3) was developed to give better girder stiffness, deepen the beam of the engine frame, and improve bearing performance.

This type of frame was used in wartime submarine types in which the cylinders were bolted up to form the beam. Smaller engines still are designed with the cylinders cast enbloc.

The design has the following disadvantages in large size engines: (a) The design is poor for the transmission of the tensile stresses; (b) large expensive steel castings or heavy iron castings are necessary to take the tension stresses; (c) casting limitations on the

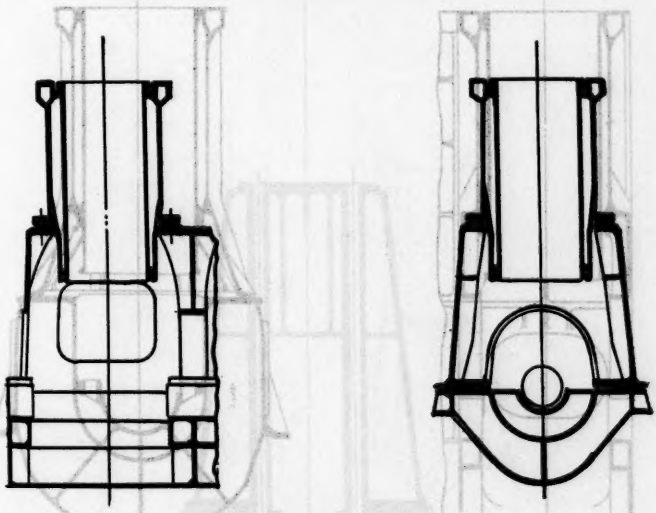


FIG. 2

larger engines demand heavy sections in unstressed parts of frame (the metal cannot cool in the mold while running to remote sections); (d) in large engines it is necessary to make the frame of a large number of smaller castings bolted together which increases the weight (flanges and bolts), is liable to create uncontrollable bending stresses, and is very expensive because of the great care necessary to properly fit and bolt the sections.

This type of framing is rapidly disappearing in cylinder sizes over 30 H. P., although it persists in the submarine engines of wartime design, and these designs still predominate in the submarines of a majority of the world's navies.

3. *The closed box frame with tie rods* (see Figure 4) or the composite frame was the next development.

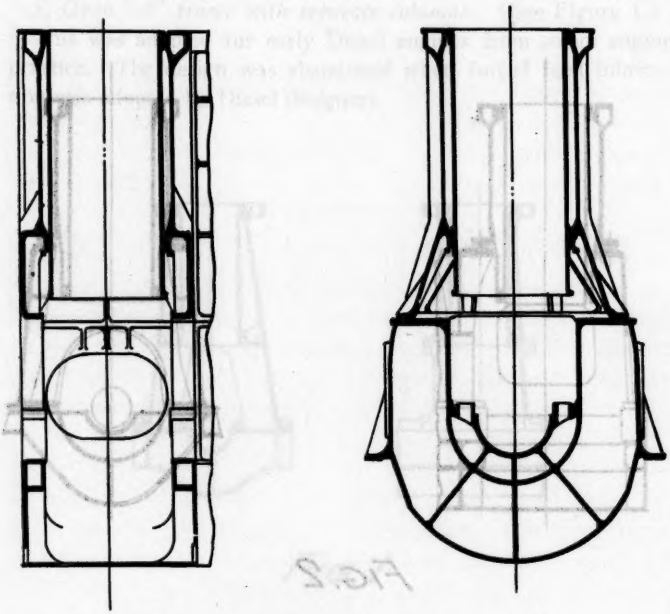


FIG. 3

The fact that cast-iron structures have a very high resistance to compressive strains, but very poor tensile strength, led to the adoption of steel alloy tie rods initially stressed to relieve the framing of the tensile strains due to the compression and explosion pressure. Iron casts very well and thin sections can be cast into the frame if it is relieved of tensile stress. (Figure 5 shows this type of frame with the very thin walls.)

The tension members or tie rods may be installed from bedplate to cylinder head, from bedplate to top of housing, from lower bearing cap to cylinder head, or from lower bearing cap to top of housing.

The partial tie rod construction is used to obviate two of the faults of tie rod construction, namely:

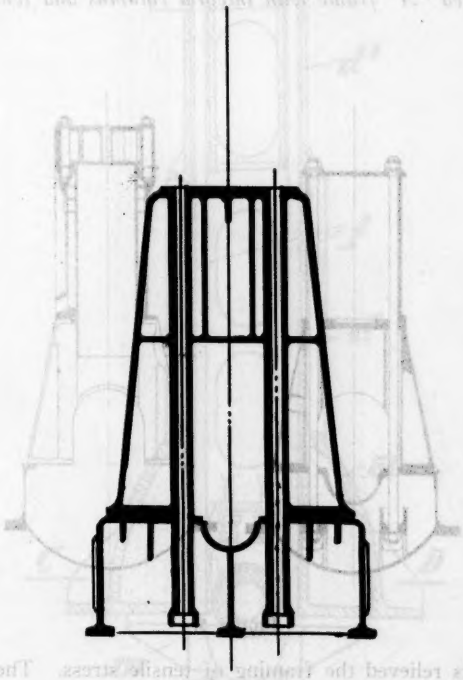


FIG. 4

(a) The "breathing" or elastic elongation of the very long tie rod which causes (1) stress oscillation in the framing and eventual failure of some joint or fitted part, or (2) noisy operation of gears due to variations in gear center distances.

(b) The difficulty of disassembling the engine due to the removal of long tie rods in confined spaces.

The partial tie rod relieves merely a part of the framing of the tensile stress and the trend is decidedly toward full tie rod construction. The above faults are overcome in other ways, for instance, (1) by careful application of initial stress and (2) by splitting the tie rod into two screwed sections to facilitate removal.

4. *Closed "A" frame with integral columns and tension members.*

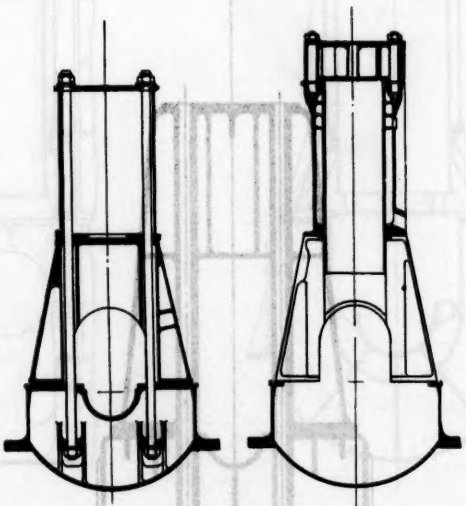


FIGURE 5.

Tie rods relieved the framing of tensile stress. The box cylinder housing only performs the functions of (1) containing the cylinder liners, (2) acting as a water jacket and (3) taking the compression.

The question immediately arises whether it is necessary to have a heavy cast iron housing to form a water jacket and compression member.

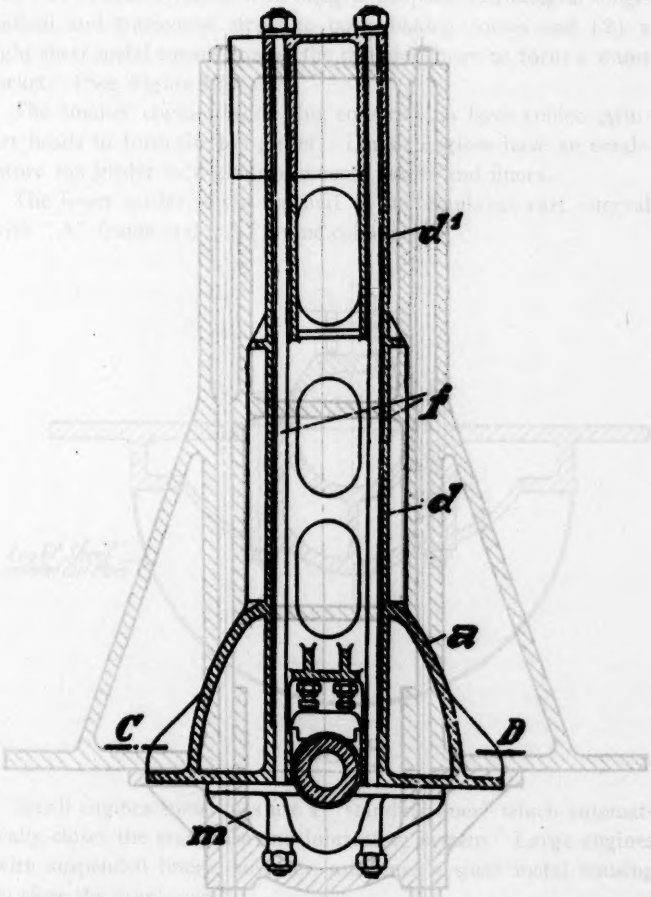


FIG. 6

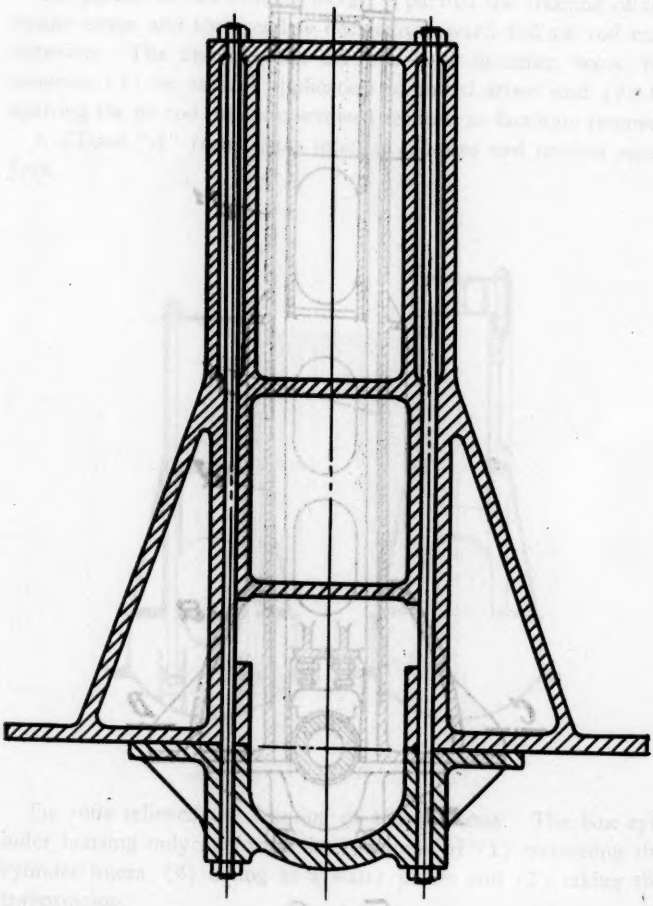


FIG. 7

The answer was the elimination of the housing by the use of (1) " A" frame columns with integral bedplate and integral longitudinal and transverse struts to take shaking forces and (2) a light sheet metal casing around the cylinder liners to form a water jacket. (See Figure 6.)

The smaller engines using this construction have enbloc cylinder heads to form the top girder. Larger engines have an entablature top girder to which are secured heads and liners.

The lower girder is the top half of the crankcase cast integral with " A" frame and " A" frame columns.

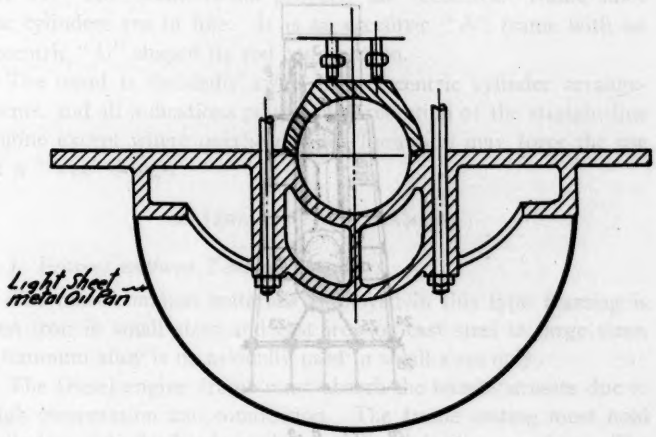


FIG. 8

Small engines sometimes use a " standing liner" which automatically closes the crankcase and lubricating system. Large engines with suspended liners, however, must use a sheet metal housing to close the crankcase.

5. *Box or " A" frame with suspended bearings and no bedplate.*

The use of tie rods led directly to suspending the bearings and eliminating the heavy crankcase bedplate. (See Figures 6-7-8.) The bedplate was replaced by a light sheet metal oil catcher.

Such a step could not have been attempted except for the fact that no bearing trouble has been experienced by the high-speed, light-weight engine since the World War designs. The bearings are very inaccessible and difficult to adjust and bearing difficulties must be eliminated before the adoption of a "bedplateless" frame.

6. *Eccentric Framing.*

Eccentric designs have been attempted and all of them effect a reduction in weight, space, or both.

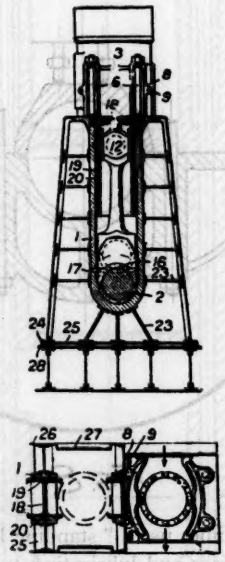


FIG. 9

Unquestionably, the straight line engine is, thus far, the only type which has attained any great success in large sizes. In the smaller sizes, below 75 H. P. per cylinder, the (1) *radial* (aircraft) and the (2) "*Vee*" (aircraft and rail car) have been more

or less successful. Notable failures have occurred in both types following attempts to increase the cylinder output.

The development of the (3) *barrel type* frame has been hindered not by framing troubles but, chiefly, by difficulty with the lubrication of moving parts.

The (4) *opposed piston frame* has given excellent service in both small and large sizes of cylinder and its corollary, the (5) *square frame* gives excellent weight saving promise, but has yet to be demonstrated in service.

A very recent type of frame is the (6) "U" frame (see Figure 9). This frame is not properly an "eccentric" frame since the cylinders are in line. It is an eccentric "A" frame with an eccentric "U" shaped tie rod construction.

The trend is decidedly away from eccentric cylinder arrangements, and all indications point to the retention of the straight-line engine except where overhead space limitation may force the use of a "Vee" design.

MATERIALS OF THE FRAMING.

1. *Frames without Tension Members.*

The most common materials employed in this type framing is cast iron in small sizes and cast iron or cast steel in large sizes. Aluminum alloy is occasionally used in small sizes only.

The Diesel engine frame must absorb the tensile stresses due to high compression and combustion. The frame casting must hold cylinders, cylinder heads, main bearings, and other members. The casting must therefore be not only very complicated but it must, at the same time, distribute the high tensile stresses. The two functions are incompatible.

To pour these complicated frames, cast iron is cheaper because of its good casting qualities. Cast iron has a low tensile strength. It was, therefore, necessary to make the iron castings excessively heavy, the frames clumsy, and of material unsuitable for the high tensile shocks.

The large submarine high-speed engines of 1917 replaced cast iron with cast steel as a framing material. Cast steel had a higher tensile strength but poor casting qualities. To obtain the benefit

of the high tensile strength of the steel it was necessary to cast the steel in thin sections. Hot steel chilled in these thin sections and there was a definite limit to minimum wall thickness of steel castings and to size of castings. Sound steel castings were very expensive. They are to-day.

The distribution of the tensile stresses over a large complicated casting leads to a deadweight of metal in unstressed sections. It is impossible in complicated cast iron or cast steel designs to determine what proportion of the total stress each wall is absorbing.

In spite of these drawbacks large cast box frames without tension members are still in vogue. In smaller sizes they predominate.

2. *Frames with Tension Members.*

This type of framing may use cast iron, cast aluminum alloy, or welded steel plate.

Cast steel no longer is used because it is expensive and its good tensile properties are no longer needed. Furthermore, the sections may now be made so thin that steel would not pour.

The problem of obtaining a suitable material is very simple in tie rod frames because of the low tensile strength requirement. *Cast iron* for frames is usually any high grade iron with an extra admixture of steel. The iron for large castings must be poured very hot. Special precaution must be taken to avoid distortion during machining.

Light frames are often made of *pearlitic* or *partial pearlitic iron* because of its good physical properties and good casting qualities.

The use of aluminum for larger Diesel frames is becoming less common. Manufacturers prefer materials under their own control and the uniformity and reliability of large aluminum castings for Diesel frames is much disputed. Builders do not like special materials produced by specialists.

Aluminum alloys are probably perfectly reliable for pistons, cylinder jackets, engine frames, or even connecting rods of small engines up to about 30 horsepower per cylinder. In large engines, aluminum's softness, high coefficient of thermal expansion, and decrease of strength with increase of temperature, all militate against its use.

Cast iron has physical properties which can be relied upon and the trend is definitely toward cast iron in tie rod frames.

The rapid entry of welding into all fields and the many welded frames seen in Europe lead to the belief that forged steel plate welded to form the Diesel frame will come increasingly into frame design of the large engines. Sections which are lightly stressed may be made as thin as desired and the metal may follow the stress line of the frame without regard to mould or casting limitations.

THE TREND IN LIGHT-WEIGHT DIESEL FRAMING.

1. *Design.*

Summing up the foregoing description of light-weight Diesel frames, it is believed that the trend in framing is as follows:

(a) Design.

1. Cylinder arrangement in line.

2. Full tension members or tie rods in all frames.

3. Box frame in small or medium sizes and (a) box frame or (b) "A" frame construction with special columns or bushings in larger sizes.

4. Suspended bearings and elimination of bedplate.

(b) Materials.

1. Aluminum or cast iron in small cylinder sizes.

2. Cast iron in medium sizes of cylinder.

3. Cast iron in large cylinder sizes or forged steel plate welded where the ultimate weight saving is desired.

(c) The future trend in large size cylinders appears to be a frame in which (1) the tensile stresses are concentrated in tie rods, (2) the compressive stresses are concentrated in a bushing or column surrounding the tie rod and integral with a welded steel skeleton frame of the "A" type, (3) the cylinder liners are suspended from a girder or entablature and the water jacket is formed of a light sheet metal casing around the liner, (4) the usual bedplate is eliminated by suspending the bearings, and (5) the lower girder and bedplate is the top half of the crankcase integral with the frame columns.

Part II.

Stresses and Strains in Engine Framings Compressed by Steel Tie Rods.

Part I shows that the use of tie rods in Diesel framing is growing. The majority of the modern refinements in framing design have been possible only through the adoption of the tension member or tie rod. It may, therefore, be of interest to describe the action of the tie rod in the Diesel frame.

The following notes on tie rod construction and calculation are printed through the courtesy of Dr. Ing. Fritz Schmidt of Kiel, a well-known German designer.

ON STRESSES AND STRAINS IN ENGINE FRAMINGS COMPRESSED BY STEEL TIE-RODS.

(The following method was described in V. D. I. Zeitschrift, 1929)

Cast-iron structures are not suitable to withstand high tensile stresses. It is possible to avoid high tensile stresses by compressing cast-iron frames with steel tie-rods. For instance, in the design of large reciprocating engines, long bolts are used connecting the girder under the main bearings with the upper frame girder, or, directly, with the cylinder cover. These bolts are fastened under high tension so that, even at the moment of the highest tensile pull in the framing, the structure is continually held under compressive stresses.

This method has recently been introduced in Diesel engine construction and many firms take advantage of this design. The frames are not subject to stresses due to the combustion pressure in the cylinder, and it is consequently possible to construct comparatively light cast-iron parts.

Extremely large engines using this design require special considerations because the elastic elongation of these long rods may possibly produce small oscillations causing severe trouble during service. The gears of the valve drive may run noisily on account of the periodic variation of the clearance between the teeth; or some joint may be overstressed causing breakage or leakage.

The following short treatise presents a simple diagram illustrating the stresses and strains in the different parts of the framing.

Without intricate calculations we are able graphically to determine the various effects when the tie-rods are being tightened and the framing subjected to combustion pressure.

To develop this diagram we introduce, from the schematic section through the frame of a Diesel engine (Figure 10), the following terms and symbols:

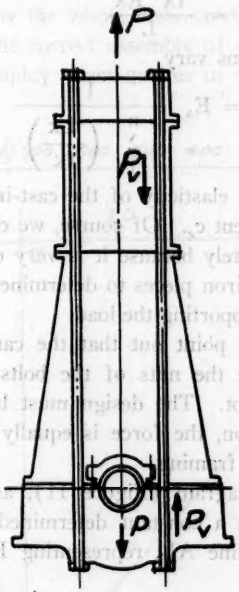


FIG. 10

P_z is the total combustion pressure *i. e.* the highest pressure during ignition. The total force P_z is, therefore, $\frac{\pi}{4} D^2 . p_z$, where p_z usually amounts to 35 – 40 atmosphere.

P_v is the initial tension of the tie-rods, *i.e.*, the compressive force acting on the engine framing after the bolts have been tightened during erection.

The elasticity of the tie-rods may be expressed by a coefficient of elasticity c_A, where the elongation, caused by the force P, is:

$$\Delta_A = \frac{P_v}{c_A}$$

If the tie-rod has the same cross section everywhere f_A, and a material with the modulus of elasticity E_A, we have the equation

$$c_A = \frac{f_A \cdot E_A}{L} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

or, if the cross sections vary

$$c_A = E_A \frac{1}{\sum_1^n \left(\frac{L_K}{f_K}\right)} \quad . \quad . \quad . \quad . \quad . \quad (1b)$$

In the same way the elasticity of the cast-iron framing is determined by the coefficient c_g. Of course, we can only calculate this coefficient approximately because it is very difficult in the different complicated cast-iron pieces to determine to what extent their walls and ribs are supporting the load.

It is important to point out that the castings must be sufficiently strong where the nuts of the bolts concentrate a great force on a small spot. The design must be such that, without noticeable deformation, the force is equally distributed over the whole section of the framing.

Developing our diagram (Figure 11), assume first, that the initial tension P_v be a constant determined by experience. At right angles to the line AB, representing P_v, we plot at B the compression of the cast-iron framing $B\,O = \Delta_g = \frac{P_v}{c_g}$, and then, from C, the corresponding extension of the tie-rod $C\,D = \Delta_A = \frac{P_v}{C_A}$

Now we trace the lines AO and DO which demonstrate a load-deformation diagram of both parts of the structure.

On the line D C we put a scale beginning in D and measuring the elongation A (mm) and above a scale with the corresponding stress. In the same manner we measure, on the line B O, the compression of the framing and beginning in E the corresponding stress.

Now our diagram indicates stress and strain when the tie-rods are tightened up but before being loaded with the combustion pressure.

The initial tension causes an elongation of the tie-rods Δ_A = D C, with the tensile stress shown on the upper scale. The framing is compressed with Δ_g = C A and loaded by Δ_g = E C'. To obtain the initial tension P_v during erection, the nut of the tie-rod has to be tightened by the whole distance A –D. This figure is very important for the correct assembly of framing and tie-rods. It is necessary to employ exact gauges in order to obtain equal load on all tie-rods.

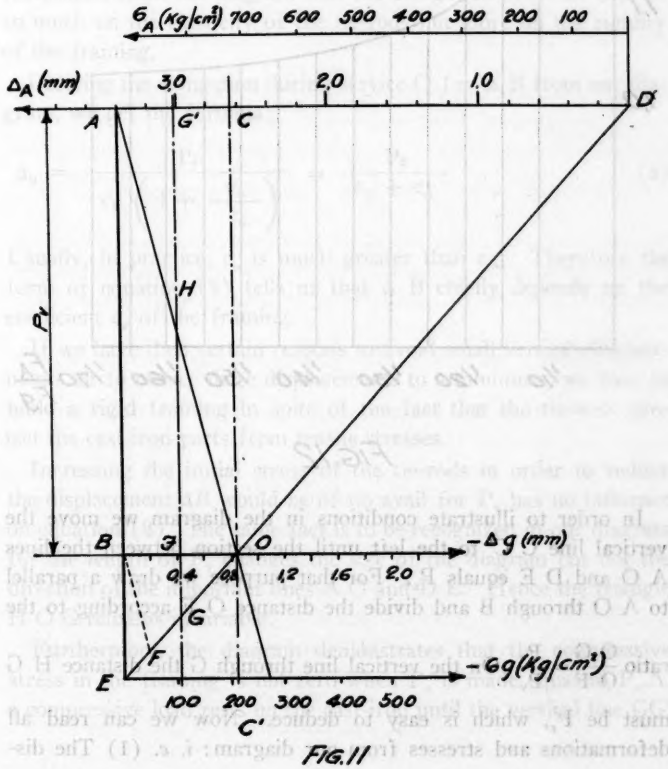


FIG. 11

During combustion in the cylinder, the whole framing is subject to stresses by the force P_z, the reaction of which acts on the cylinder cover.

The tie-rods are now subject to an additional stress, a small elongation of the whole framing with the steel-rods takes place, and the compressive stress in the framing is diminished.

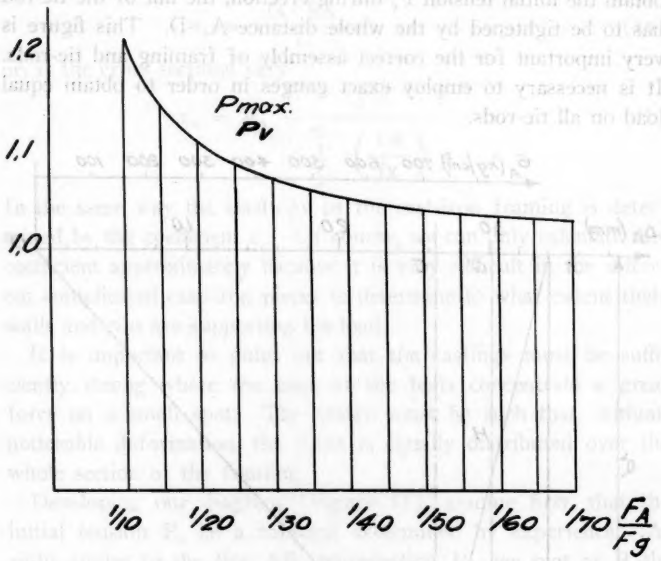


FIG. 12

In order to illustrate conditions in the diagram we move the vertical line C C′ to the left until the section between the lines A O and D E equals P_z. For that purpose we draw a parallel to A O through B and divide the distance O F according to the ratio $\frac{O\,G}{O\,F} = \frac{P_z}{P_v}$ On the vertical line through G the distance H G must be P_z, which is easy to deduce. Now we can read all deformations and stresses from our diagram: *i. e.* (1) The dis-

tance O J represents the vertical elongation of the whole framing during ignition, (2) G′ H is the compressive load (kilograms) remaining at this moment on the cast-iron, (3) the corresponding compressive stress can be read on the scale below, (4) the total elongation of the tie-rods is shown by DG′ with the tensile stress above, (5) the corresponding load in kilograms is represented by GG′.

In discussing these results we can recognize some facts which very often are neglected or misunderstood. At first it must be pointed out, that even under the highest initial stress of the tie-rods the framing is strained when combustion takes place. It is recognized from the diagram that the elongation does not depend so much on the elasticity of the tie-rods but more on the rigidity of the framing.

Deriving the elongation during service O J = Δ B from our diagram, we get the formula:

$$\Delta_B = \frac{P_z}{c_g \left(1 + \frac{c_A}{c_g}\right)} = \frac{P_z}{c_g + c_A} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Usually, in practice, c_g is much greater than c_A. Therefore the form of equation (2) tells us that Δ B chiefly depends on the coefficient c_g of the framing.

If we have then certain reasons to avoid small vertical displacements, or to reduce these displacements to a minimum, we have to build a rigid framing in spite of the fact that the tie-rods protect the cast-iron parts from tensile stresses.

Increasing the initial stress of the tie-rods in order to reduce the displacement ΔB would be of no avail for P_v has no influence on equation (2). The same fact is to be recognized in our diagram for the length of P_v changes the size of the diagram but not the direction of the important lines A O and D E. Hence the triangle H O G remains invariable.

Furthermore, the diagram demonstrates that the compressive stress in the framing is not zero when P_z is made equal to P_v.A, a compressive load rests on the cast-iron until the vertical line GG′

coincides with the base-line A E, or until the force P_z has increased to the length AE. Calculating this length we get

$$P_{max} = P_v \left(1 + \frac{c_A}{c_g}\right) \quad \ldots \ldots \ldots \ldots \quad (3a)$$

Now we assume (1) that the modulus of elasticity:

for cast-iron is $E_g = 1000\ 000$ kg/cm²

and for steel is $E_A = 2200\ 000$ kg/cm²

and (2) that the elastic length of both structural parts are equal and their cross sections are reduced to constant figures F_g and F_A. Then equation (3ª) is transformed to:

$$P_{max} = P_v \left(1 + \frac{2.2\ F_A}{F_g}\right)$$

Figure 12 shows the values $\frac{P_{max}}{P_v}$ plotted against $\frac{F_A}{F_g}$ as abscissae .

For a normal ratio $\frac{F_A}{F_g} = \frac{1}{20}$ to $\frac{1}{40}$ and the maximum load which the structure can stand would be 10-15 per cent higher than the initial tension of the tie-rods, or, inversely, the initial tie-rod tension could be about 10 per cent smaller than the combustion force.

Naturally, in practice, the ratio $\frac{P_z}{P_v}$ will, for safety's sake, be made much lower than 1.1 because allowance must be made for the fatigue of material, the small errors in calculation, and unequal tightening of the tie-rods.

Finally, we see in our diagram that, during the action of combustion, the stress in the tie-rod exceeds the initial tension. Obviously the more this excess in tie-rod stress the smaller the stiffness of the framing *i. e.*, the smaller the coefficient c_g. We can easily deduce this small increase of stress from the diagram, and if we calculate the ratio to the original initial stress we get the equation:

$$\frac{\Delta\, \delta_A}{\delta_v} = \frac{P_z}{P_v} \frac{1}{\left(1 + \frac{c_g}{c_A}\right)}$$

which means that the momentary stress depends on the ratio $\frac{c_g}{c_A}$. If the framing is rather rigid compared with the elasticity of the tie-rods, $\Delta\sigma_A$ becomes very small and the stress in the tie-rods is almost invariable. Inversely a weak framing causes a rather high additional stress during ignition.

Equation (3^a) shows that with a weak frame the ratio $\frac{P_{max}}{P_v}$ increases. On account of these facts, if the framing is weak and elastic, it is advisable to reduce the initial stress of the tie-rods, $\frac{P_v}{P_z}$ is made only 1.1 to 1.2 in order to avoid a high maximum stress during ignition. In spite of this reduction of P_v this tie-rod design is as reliable as one with a rigid framing and higher initial tension because the margn of P_{max} over P_z remains the same in each case.

CONDENSER SCOOPS IN MARINE INSTALLATIONS.

By H. J. Hanzlik, Member.

Cooling water in marine condensers is supplied either by means of main circulating pumps or by means of scoops, the system employed depending primarily on the speed of the vessel. Main circulating pumps are used in vessels having low speed and which, of necessity, are required to maneuver a good deal. Scoops are more applicable to higher speed ships, which are required to make long runs at high speed, such as passenger and war vessels. On vessels where scoops are provided, there is also an auxiliary method furnished to take care of the circulating water supply when the vessel is running at low speeds, or is maneuvering. This auxiliary system may consist either of a pump or an ejector.

The scoop method has an advantage over the pump method from a reliability point of view, as it reduces the number of parts. As to efficiency, scoops are as economical as main circulating pumps if the latter are motor-driven and more economical if the latter are turbine-driven. On the other hand scoops are at a slight disadvantage when it comes to regulating the flow of circulating water through the system which may be desired in zones of warmer temperature in the oceans.

Three scoop methods have been developed in marine practice to date; namely, those employing as an auxiliary either a centrifugal pump, or a propeller-type pump or an ejector. Each of the three types, described in this article, has certain advantages and disadvantages of its own.

CONVENTIONAL DESIGN OF SCOOP EMPLOYING CENTRIFUGAL PUMP AS AN AUXILIARY.

Figure 1 illustrates a scoop installation having a centrifugal pump as an auxiliary. Water is circulated through the condenser system by this pump only when the vessel is proceeding at slow

speed, or when maneuvering. The main injection and overboard discharge piping follows as direct a course as possible with passages maintained at practically constant area when the scoop is in service. The velocity of the circulating water is controlled by a swinging check valve which is not fully opened when the velocity of injection water is low. The auxiliary pump is placed in a by-pass pipe of smaller size than the scoop piping. The by-pass piping is made with as few bends as possible in order to minimize the resistance of the flow when the auxiliary pump is operating.

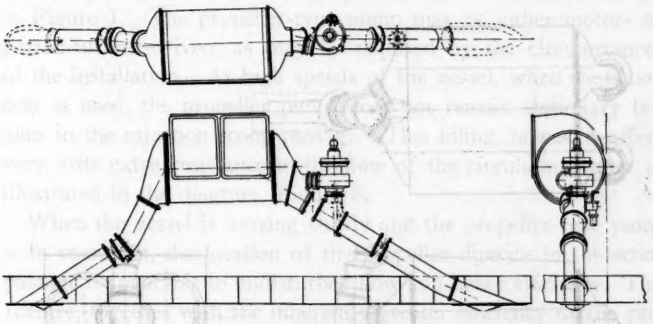


FIGURE 1.

In the arrangement shown in Figure 1 the high placement of the condenser results in long injection and overboard discharge passages. The passages are usually given a gentle slope to provide an easy approach and discharge for the circulating water. This slope of the overboard discharge pipe is somewhat objectionable as it offers increased resistance to flow when the ship moves astern.

These long injection and overboard discharge passages have the advantage in affording convenient locations for standard gate valves for the shutting off of circulating water in case the condenser tubes have to be cleaned, examined or repaired.

Excessive length of these passages necessitates the cutting of a number of frames, which are the strength members of the ship, When these are cut, additional reinforcements are required which tend to increase the expense and the weight of the installation.

The gate valves permit partial or complete closing of these passages, which is ofttimes desirable. There is one check valve and one gate valve in the injection passage and one gate valve in the discharge. The check valve closes automatically when changing over from the scoop to the auxiliary system. When a scoop is used, the rush of water through the injection passage keeps the check valve open. Both injection and discharge pipes have a lip projecting through the vessel body, which is supposed to improve the flow of circulating water in and out of these passages.

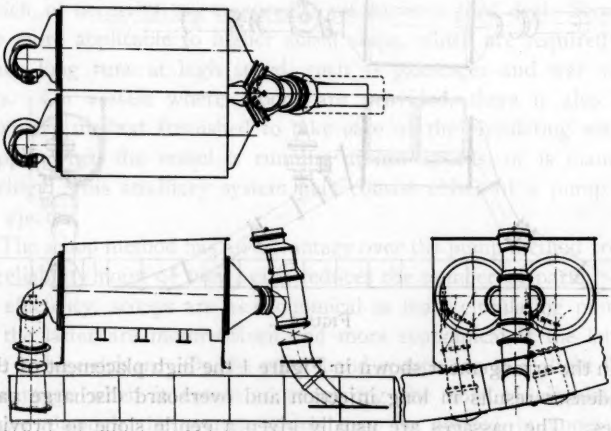


FIGURE 2.

NEW DESIGN OF SCOOP EMPLOYING PROPELLER PUMP AS AN AUXILIARY.

Some recent tests conducted by H. F. Schmidt at the Westinghouse Company Research Laboratories have shown the distinct improvements that can be made in the design of condenser scoops and auxiliary circulating pumps, both in efficiencies and weight. Early experiments of Schmidt's are described in the JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS, February, 1930, issue.

For the purpose of comparison, we have shown in Figure 2, condensing equipment of about the same size as the equipment illustrated in Figure 1. In this arrangement there is one injection scoop with a gate valve provided, common to the two tube nests employed in this case, and two overboard discharge pipes, each having a special angle check valve. Circulating water is supplied to this condenser by means of scoops of a special design. The auxiliary circulating pump is of the propeller type, and it is placed in the injection scoop passage direct, without the use of by-pass piping, such as is employed in the construction shown in Figure 1. The propeller-type pump may be either motor- or geared-turbine-driven, as may be required by the circumstances of the installation. At high speeds of the vessel, when the scoop only is used, the propeller pump does not remain stationary but idles in the injection scoop passage. This idling, however, offers very little extra resistance to the flow of the circulating water as illustrated in the diagram, Figure 3.

When the vessel is moving slowly and the propeller-type pump is in operation, the location of the propeller directly in the scoop passage is favorable to undisturbed flow and hence efficiency. This feature, together with the inherently greater efficiency of the propeller-type pump, results in more efficient auxiliary operation than that afforded by the apparatus shown in Figure 1. The condenser shown in Figure 2 is an underneath condenser, which is usually located low down in the vessel thus making it possible to have short injection and overboard discharge passages. In an effort to shorten the length of the engine room to a minimum, to reduce the number of ship frames to be cut, to permit bringing the turbine and gears closer together and to save the weight of the circulating water piping, the following radical departures in design have been introduced in this newer scoop system:

(1) The customary lip on the injection scoop is omitted. This feature eliminates considerable resistance to flow, and also minimizes the possibility of closing up the mouth of the injection passage should the ship strike an obstruction. Recent experiments, conducted by Schmidt, have demonstrated that the efficiency of the "lipless" scoop is only slightly less than the efficiency of the "lip" scoop.

(2) The injection duct is inclined to a more acute angle and is built with a slight curvature, flaring out with an increasing area as it approaches the pump. While the bend in the duct means an increase in resistance, this loss is more than offset by the gain obtained through the gradual increase in area of this duct. The flaring of the duct reduces the velocity of the water after it passes

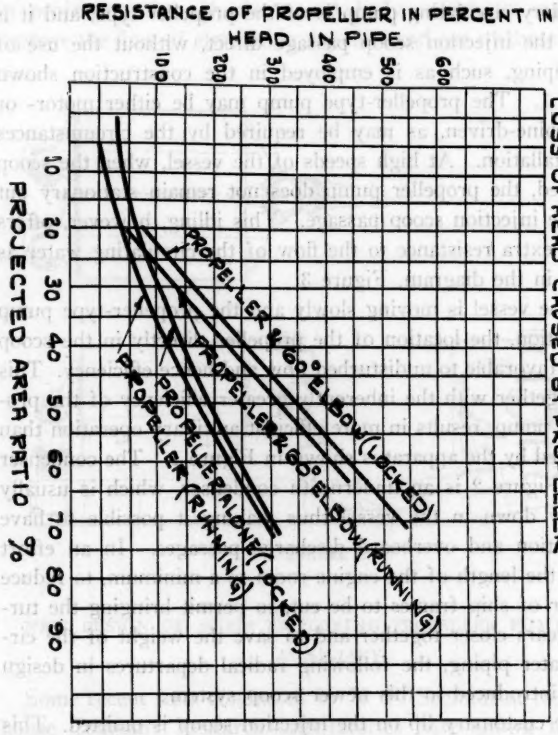


FIGURE 3.

at high speed through the small mouth of the injection passage, and thus properly converts velocity into pressure. In the scoop shown in Figure 1, the conversion of velocity into pressure does not take place until the circulating water reaches the waterbox,

and then only very inefficiently. This is because in the conventional scoop, for pipe sizes practicable of application, the water velocity is so low that little or no conversion can take place regardless of the shape of the waterbox.

(3) The overboard discharge likewise is short, being practically vertical, and is provided with a small projection on the forward side. This projection is necessary to prevent a back pressure being built up by the flow of water past the discharge, and tests have shown that it is needed whether the overboard discharge is at right angles to the ship skin or inclined in the aft direction. The overboard discharge at right angles has the advantage in that the same size of lip produces more suction than in the case of the inclined overboard discharge. It also offers less back pressure or resistance to flow in the astern direction, when the ship is receiving backwash from the propeller.

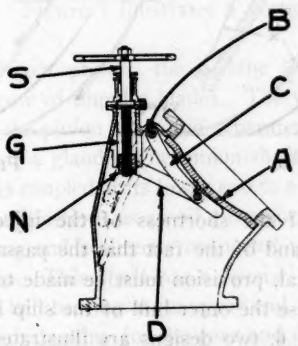


FIGURE 4.

(4) The overboard discharge passage has an increasing area outward to get a more efficient conversion of velocity into pressure.

(5) Because of the shortness of the overboard discharge passage, in many cases it is necessary to replace the standard gate valve by a special screw-operated angle check valve, illustrated in Figure 4. There is a slight disadvantage in using this valve on account of its inability to stay in partly opened position without having a tendency to chatter. It is held locked, therefore,

in the fully opened or fully closed position. Otherwise, it meets all the requirements of the standard gate valve, and has the added advantages of lightness and greater compactness.

This valve consists of a disc (a) that swings about an axle (b) guided by two arms (c). The valve is operated by a screw (s) working in a trunnion nut (n) with guides (g) and rollers on the end of the trunnions. Motion of the trunnion nut is imparted to the valve disc by means of two connecting links (d). The valve has the advantage that it closes automatically should either the valve stem of the screw break.

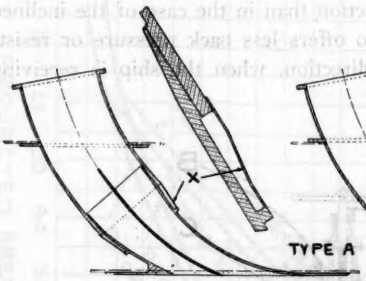


FIGURE 5.

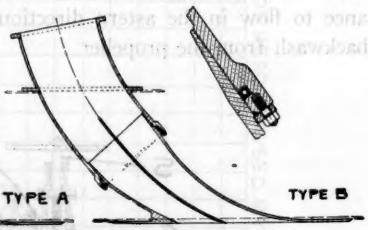


FIGURE 6.

(6) Because of the shortness of the injection and the discharge passages, and of the fact that the passages are vertical or very nearly vertical, provision must be made to prevent injury to water boxes in case the outer hull of the ship hits an obstruction. In Figures 5 and 6, two designs are illustrated that permit telescoping of ducts with alternates as to the method of fastening to the inner bottom. These drawings show such construction as applied to the injection scoop. The same form of joint is used also on the overboard discharge pipes.

Type (A) consists of a sliding sleeve (X) covered by a copper band, about 1/8 inch thick, brazed to the outer and inner portion of the scoop pipe. This band is carefully annealed, so as to crush with a minimum force and without cracking, as otherwise leakage would result should the injection duct be struck and pushed

forward. On a large vessel, a construction may easily be provided that permits duct telescoping of twelve inches without injury to the condenser waterboxes.

Type (B) has a machined sliding fit made watertight for emergency by a cup washer expanded by a small internal bronze spring, the hole being filled with tallow. Normal water-tightness is obtained by a rubber ring held in place by a retaining ring. This style of joint allows much smaller openings in the skin and inner bottoms than the older designs, since the inner portion can be put in place from the inside and the outer portion from the outside and the joint bolted in position. The same advantage applies to the copper sleeve type (A) joint, if the upper joint of the sleeve can be silver-soldered after it is assembled in the vessel.

(7) The auxiliary centrifugal circulating pump is replaced by a more efficient geared motor- or turbine-driven propeller-type pump. Location of the pump may be in a vertical, slanting or horizontal position. Figure 7 illustrates a vertical turbine-driven pump arrangement.

In the turbine-driven pumps, the turbine is of the re-entry type with a single row of impulse blades. The wheel is overhung and is mounted on the pinion shaft and separated from the pinion housing by means of a gland. The pinion-shaft has two babbitt-lined bearings and is coupled at its lower end to a centrifugal lubricating oil pump that functions as an oil governor at the same time. The gear is overhung and is directly connected to the shaft of the propeller-type pump. This shaft has a special rubber bearing at its lower end and a ball bearing at its upper end. The ball bearing besides being a steady bearing for the gear and pump shaft is also a thrust bearing for the whole rotating element which includes the turbine pinion, pump and gear shafting. The turbine is controlled by an oil governor actuated by the previously mentioned lubricating oil pump. The turbine and gear housings are of welded-steel construction and the pump housing and runner are castings. The relief valve safeguards the turbine housing against excessive steam pressure.

When the ship is under full speed the propeller-type pump idles at nearly full speed with steam shut off but the lubricating system

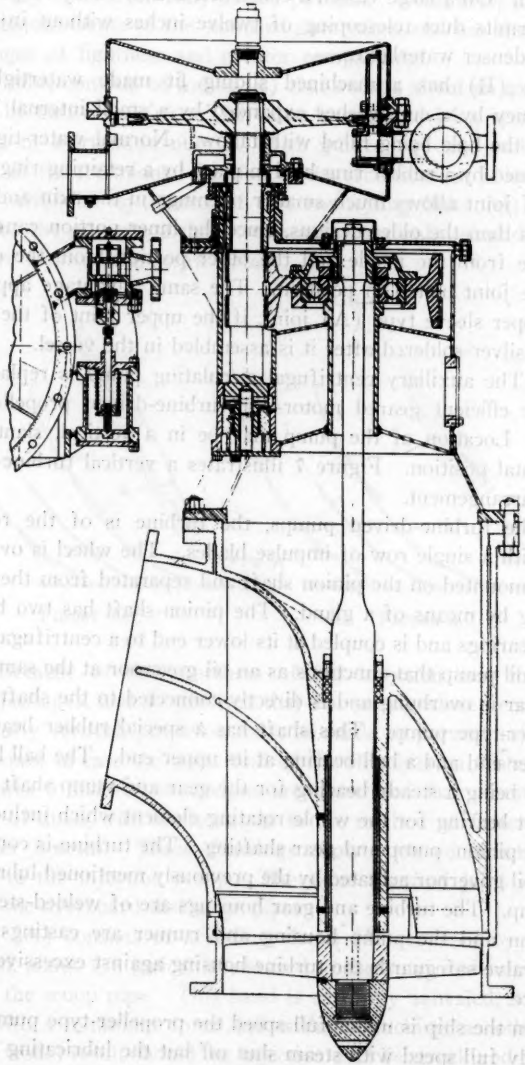


FIGURE 7.

is in operation. An advantage of this new system is that the propeller pump may be operated in conjunction with the scoop, when the speed of the ship is low or if the ship is in tropical waters where increased circulation is required. The old conventional design of scoop employing auxiliary centrifugal pump located in by-pass piping does not offer this advantage.

NEW DESIGN OF SCOOP EMPLOYING EJECTOR AS AN AUXILIARY.

As third alternative, the new design scoop described may be used with a water ejector as an auxiliary for moving water through the circulating system during maneuvering periods. For this arrangement, the ejector is connected to some high-pressure pump of the ship and may be placed in the sloping part of the scoop as shown in Figure 8.

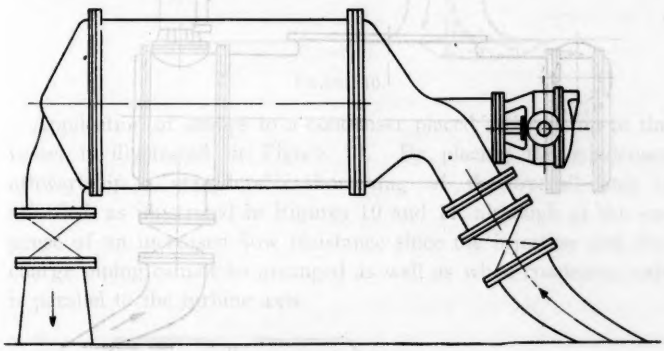


FIGURE 8.

The ejector has the advantage in not requiring any rotating parts in the system, and its construction is very simple. Its efficiency, however, is not as high as that of the propeller-type pump, because of the lower efficiency of the ejector itself and of the restriction of the injection passage necessary to accommodate the ejector.

The ejector system may also be operated in series with the scoop when the ship is proceeding at reduced speed or is in need of additional circulating water as would be the case in the tropics.

SPECIAL APPLICATIONS OF NEW DESIGN SCOOPS.

Figure 8 illustrates an arrangement with the propeller pump shafting in a horizontal position. When the vessel is maneuvering, water is lifted by the propeller-type pump into the forward waterbox, from which it flows through the tubes to the aft waterbox and out through the overboard discharge. Standard gate valves are employed in both the injection and the discharge passages.

In Figure 9, the propeller pump is placed in the forward waterbox. This design improves the flow of the circulating water somewhat at the expense of greater head room and wider injection waterbox.

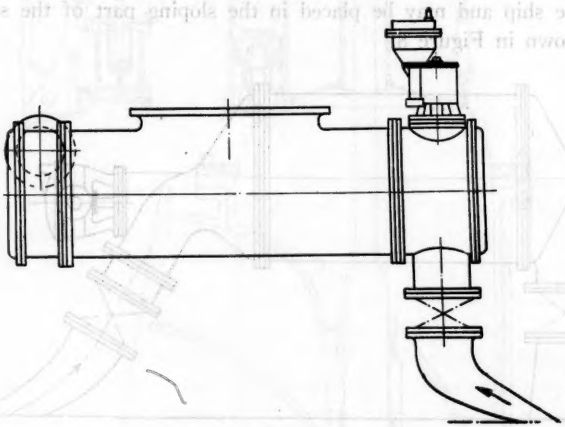


FIGURE 9.

Figure 10 shows the propeller pump placed in a central core of the condenser. By this arrangement, water enters this central passage by means of the scoop from which it flows aft into the aft waterbox, then forward through the condenser tubes into the forward waterbox and out through the overboard discharge piping. This arrangement has a greater flow resistance, but it permits placing of the turbine close to the reduction gear or generator, thus making the overall length of the unit considerably

shorter. Injection scoop, inlet and overboard discharge outlet are placed close together. In this illustration, the scoop is of the older style with an injection lip.

Figure 11 shows the same general arrangement as Figure 10, but with an ejector as an auxiliary.

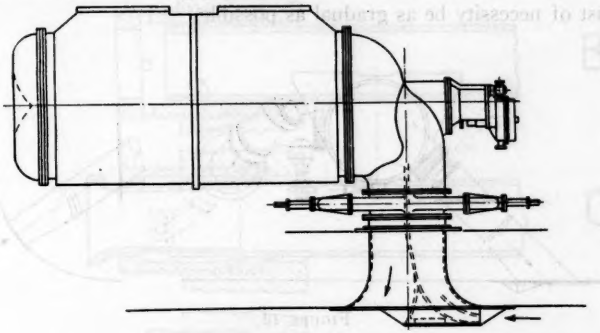


FIGURE 10.

Application of scoops to a condenser placed athwartship in the vessel is illustrated in Figure 12. By placing the condenser athwartship a considerable shortening of the overall unit is afforded, as illustrated in Figures 10 and 11, although at the expense of an increased flow resistance since the injection and discharge piping cannot be arranged as well as when condenser axis is parallel to the turbine axis.

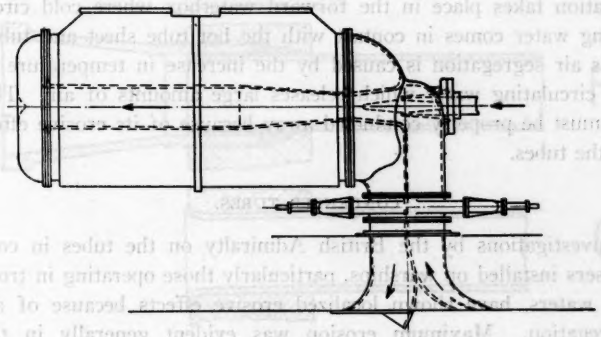


FIGURE 11.

CONDENSER WATERBOXES.

Condenser waterboxes are fundamentally an extension of the injection and overboard discharge piping and consequently should be designed with equal care. Water must be brought into them with the minimum amount of turbulence and the changes in area must of necessity be as gradual as possible.

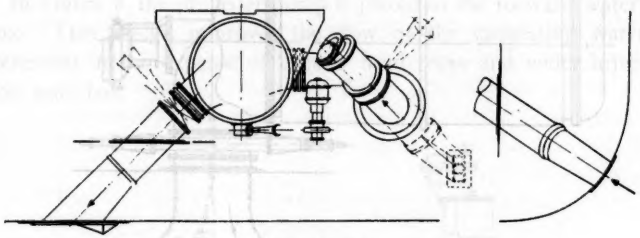


FIGURE 12.

In "side" condenser arrangement, where the slope of the injection and discharge piping is very gentle, the water generally enters and leaves at the bottom of waterbox without a turn. In "underneath" condensers with the propeller-type pump located in the injection passage it is more convenient to have the injection piping enter the water box at an angle of 100 degrees or if possible 120 degrees and overboard piping leave at the center of waterbox or as low as possible with a 90 degree turn. Considerable air segregation takes place in the forward waterbox where cold circulating water comes in contact with the hot tube sheet and tubes. This air segregation is caused by the increase in temperature of the circulating water which releases large amounts of air. This air must be properly conducted away because of its erosive effect on the tubes.

CONDENSER TUBES.

Investigations by the British Admiralty on the tubes in condensers installed on warships, particularly those operating in tropical waters, have shown localized erosive effects because of air segregation. Maximum erosion was evident generally in the

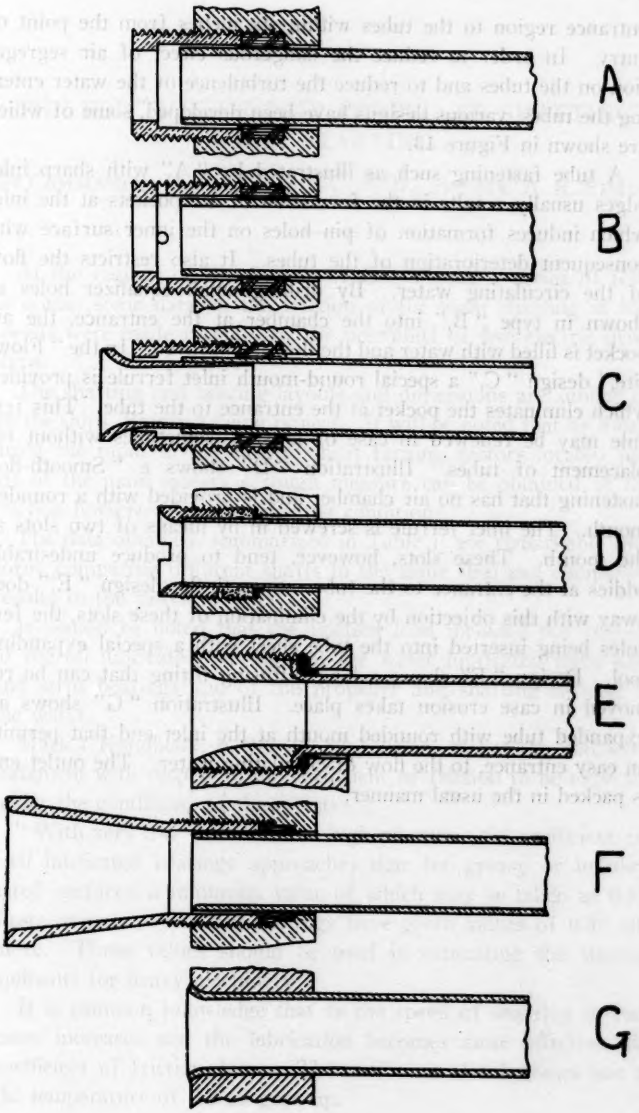


FIGURE 13.

entrance region to the tubes within six inches from the point of entry. In order to reduce the dangerous effect of air segregation on the tubes and to reduce the turbulence of the water entering the tubes, various designs have been developed, some of which are shown in Figure 13.

A tube fastening such as illustrated by "A" with sharp inlet edges usually results in the formation of air pockets at the inlet which induces formation of pin holes on the inner surface with consequent deterioration of the tubes. It also restricts the flow of the circulating water. By drilling small equalizer holes as shown in type "B," into the chamber at the entrance, the air pocket is filled with water and the flow is improved. In the "Flow-rite," design "C," a special round-mouth inlet ferrule is provided which eliminates the pocket at the entrance to the tube. This ferrule may be renewed in case of erosion, sometimes without replacement of tubes. Illustration "D" shows a "Smooth-flo" fastening that has no air chamber and is provided with a rounded mouth. The inlet ferrule is screwed in by means of two slots at the mouth. These slots, however, tend to produce undesirable eddies at the entrance to the tube. Smooth-flo, design "E," does away with this objection by the elimination of these slots, the ferrules being inserted into the tube sheet with a special expanding tool. Design "F" shows a long diffusing fitting that can be removed in case erosion takes place. Illustration "G" shows an expanded tube with rounded mouth at the inlet end that permits an easy entrance, to the flow of circulating water. The outlet end is packed in the usual manner.

THE FRICTION OF SHIP PROPELLER SHAFTING WHEN STARTING.

By Commander H. F. D. Davis, U. S. N., and Mr. A. R. Shedd.

At the request of the Bureau of Engineering a series of tests to obtain some data on the friction of the main shafting at low speeds were made recently by the personnel of five electric drive ships.

The shafting and bearing layouts and dimensions are similar on all the ships, Figure 1 being typical. It will be noted that by measuring the input to the electric shaft turning motors located just aft of the main motors a rough measure can be obtained of the friction horsepower under starting conditions.

The data obtained, summarized in Table I, are remarkably uniform, comparing different shafts in the same ship and comparing results in the different ships.

It should be noted that the friction load included the friction of the oil lubricated bearings, of the water lubricated stern tube and strut bearings and of the propeller and shafting turning in the water.

Mark's Handbook, p. 245 of 3d Edition, makes the following statement with respect to the coefficient of friction to be expected under the conditions of these tests:

"With very low velocities and high pressures the coefficient for well lubricated bearings approaches that for greasy or unlubricated surfaces, a minimum value of which may be taken as 0.15. Tests of new, well fitted bearings have given values of 0.30 and more. These values should be used in estimating the starting moments for heavy machinery."

It is common knowledge that as the speed of shafting in such cases increases and the lubrication becomes more effective, the coefficient of friction drops. The coefficient also becomes less as the temperature of the oil goes up.

TABLE I

Outboard Shafts Nos. 1 and 4

Ship	Speed Reduction Ratio	Type Speed Reduction	Shaft No. 1					Shaft No. 4				
			Main Shaft R.P.M.	Turning Motor Input: H. P.	Elect. Eff.	Gear Eff.	Output: H.P.	Main Shaft R.P.M.	Turning Motor Input: H. P.	Elect. Eff.	Gear Eff.	Output Eff.
A	1470 to 1	one double	.1225	4.7	.86	.80	3.23	.109	3.84	.83	.80	2.55
		one single	.1735	4.55	.85	.80	3.10	.1570	3.52	.82	.80	2.31
		worm	.2570	4.07	.83	.80	2.7	.2490	3.19	.815	.80	2.08
B	1470 to 1	one double	.163	5.1	.85	.80	3.47	.182	4.7	.875	.80	3.29
		one single	.187	5.43	.86	.80	3.74	.206	5.3	.87	.80	3.69
		worm	.206	5.75	.87	.80	4.0	.227	5.9	.855	.80	4.04
C	1470 to 1	one double										
		one single										
		worm	.205	4.47	.80	.80	2.86	.19	3.98	.85	.80	2.71
D	4200 to 1	one spur gear	.081	3.95	.84	.75	2.49					
		two single worms	.121	4.0	.84	.75	2.52					
			.141	4.0	.84	.75	2.52					
E	4200 to 1	one spur gear	.102	4.18	.84	.75	2.63	.114	3.62	.835	.75	2.27
		two single worms	.13	4.18	.84	.75	2.63	.137	3.46	.83	.75	2.16
			.14	4.18	.84	.75	2.63	.147	3.46	.83	.75	2.16

Inboard Shafts Nos. 2 and 3.

A	1470 to 1	one double	.1565	4.35	.85	.80	2.96	.0932	5.59	.87	.80	3.89
		one single	.1835	4.02	.84	.80	2.7	.1463	5.3	.865	.80	3.67
		worm	.2280	3.57	.82	.80	2.34	.2130	5.03	.86	.80	3.46
B	1470 to 1	one double	.160	3.8	.86	.80	2.61	.153	4.8	.87	.80	3.34
		one single	.174	4.15	.84	.80	2.79	.183	5.08	.86	.80	3.5
		worm	.190	5.43	.83	.80	3.61	.200	5.6	.855	.80	3.83
C	1470 to 1	one double										
		one single										
		Worm	.194	5.78	.86	.80	4.07	.194	4.89	.86	.80	3.36
D	4200 to 1	one spur gear						.089	6.1	.87	.75	4.03
		two single worms						.107	6.3	.87	.75	4.11
								.121	6.3	.87	.75	4.11
E	4200 to 1	one spur gear	.101	5.02	.86	.75	3.24	.102	4.34	.85	.75	2.77
		two single worms	.119	4.7	.855	.75	3.01	.125	4.2	.845	.75	2.66
			.137	4.38	.85	.75	2.8	.140	4.2	.845	.75	2.66

TABLE II

OUTBOARD SHAFTS NOS. 1 and 4

$2 \pi Pr n f_1 / 12 \times 33000 =$ Friction horsepower

	P Estimated Loads Pounds	r Radius Shaft Inches	l Length Bearing Inches	P/2 rl Normal Press. lbs/in²	No. 1 Shaft $2 \pi Pr n / 12 \times 33{,}000$			No. $2 \pi Pr$
					n = .1225	n = .1735	n = .8570	n = .1090	n
Motor - for'd.	24,557	7.50	20	81.9	.358	.507	.751	.319	
" Aft	27,069	7.50	20	90.2	.395	.559	.828	.351	
Thrust - for'd	5,266	7.75	16.5	20.6	.079	.112	.166	.071	
" "	5,266	7.75	16.5	20.6	.079	.112	.166	.071	
Spring No. 1	4,774	7.75	13.125	23.5	.072	.102	.151	.064	
" "	6,090	7.75	13.125	30.0	.092	.130	.192	.082	
Stern tube - for'd:	15,811	9.56	48	17.2	.254	.416	.617	.262	
" " aft	22,566	9.56	60	19.7	420	.594	.880	.373	
Strut	28,510	9.56	72	20.7	.530	.751	1.112	.472	
			TOTALS		2.319	3.283	4.862	2.065	3
Net friction H. P. from Table I, cols. 8 and 23					3.23	3.10	2.7	2.55	2
f_1 = net friction H.P. ÷ $2 \pi Pr n/12 \times 33.000$									
n = rough average coefficient of friction					1.393	.944	.555	1.235	

INBOARD SHAFTS NOS. 2 and 3

$2 \pi Pr n f_1/12 \times 33000 =$ Friction horsepower

	P Estimated Loads Pounds	r Radius Shaft Inches	l Length Bearing Inches	P/rl Normal Press. Lbs/in²	No. 2 Shaft $2 \pi Pr n/12 \times 33000$			No. 3 $2 \pi Pr n/$
					n = .1565	n = .1835	n = .2880	n = .0932	n =
Motor - for'd.	24,557	7.50	20	81.9	.457	.536	.666	.272	.4
" aft	27,069	7.50	20	90.2	.504	.591	.735	.300	.4
Thrust - for'd.	5,266	7.75	16.5	20.6	.101	.119	.148	.060	.0
- aft	5,266	7.75	16.5	20.6	.101	.119	.148	.060	.0
Spring No. 1	7,277	7.75	13.125	35.9	.140	.164	.204	.083	.1
" " 2	7,650	7.75	13.125	37.7	.147	.173	.215	.088	.1
" " 3	7,650	7.75	13.125	37.7	.147	.173	.215	.088	.1
" " 4	7,458	7.75	13.125	36.8	.144	.168	.209	.085	.1
Stern tube for'd.	15,811	9.56	48	17.2	.376	.440	.547	.224	.3
" " aft	22,566	9.56	60	19.7	.536	.628	.781	.319	.5
Strut	28,510	9.56	72	20.7	.677	.794	.986	.403	.6
			TOTALS		3.330	3.905	4.854	1.982	3.1
Net friction H.P. from Table I, cols. 13 and 18.					2.96	2.70	2.34	3.89	3.0
f_1 = Net friction H.P. ÷ $2 \pi Pr n/12 \times 33000$									
n = rough average coefficient of friction					.889	.691	.482	1.963	1.1

	No. 4 Shaft 2 V Pre/12 x 33,000		
= .1090	n = .1870	n = .2650	
.319	.547	.788	
.351	.602	.852	
.071	.121	.161	
.071	.121	.161	
.064	.110	.146	
.082	.140	.187	
.262	.449	.597	
.373	.640	.859	
.472	.809	1.077	
.065	3.539	4.712	
.55	2.31	2.08	
.295	.653	.441	

	No. 3 Shaft 2 V Pre/12 x 33000	
.0932	n = .1463	n = .2130
.272	.428	.623
.300	.471	.686
.060	.095	.138
.060	.095	.138
.083	.131	.191
.086	.138	.200
.086	.138	.200
.085	.134	.195
.324	.351	.511
.319	.501	.729
.403	.633	.922
.962	3.115	4.533
.89	3.67	3.46
.963	1.178	.763

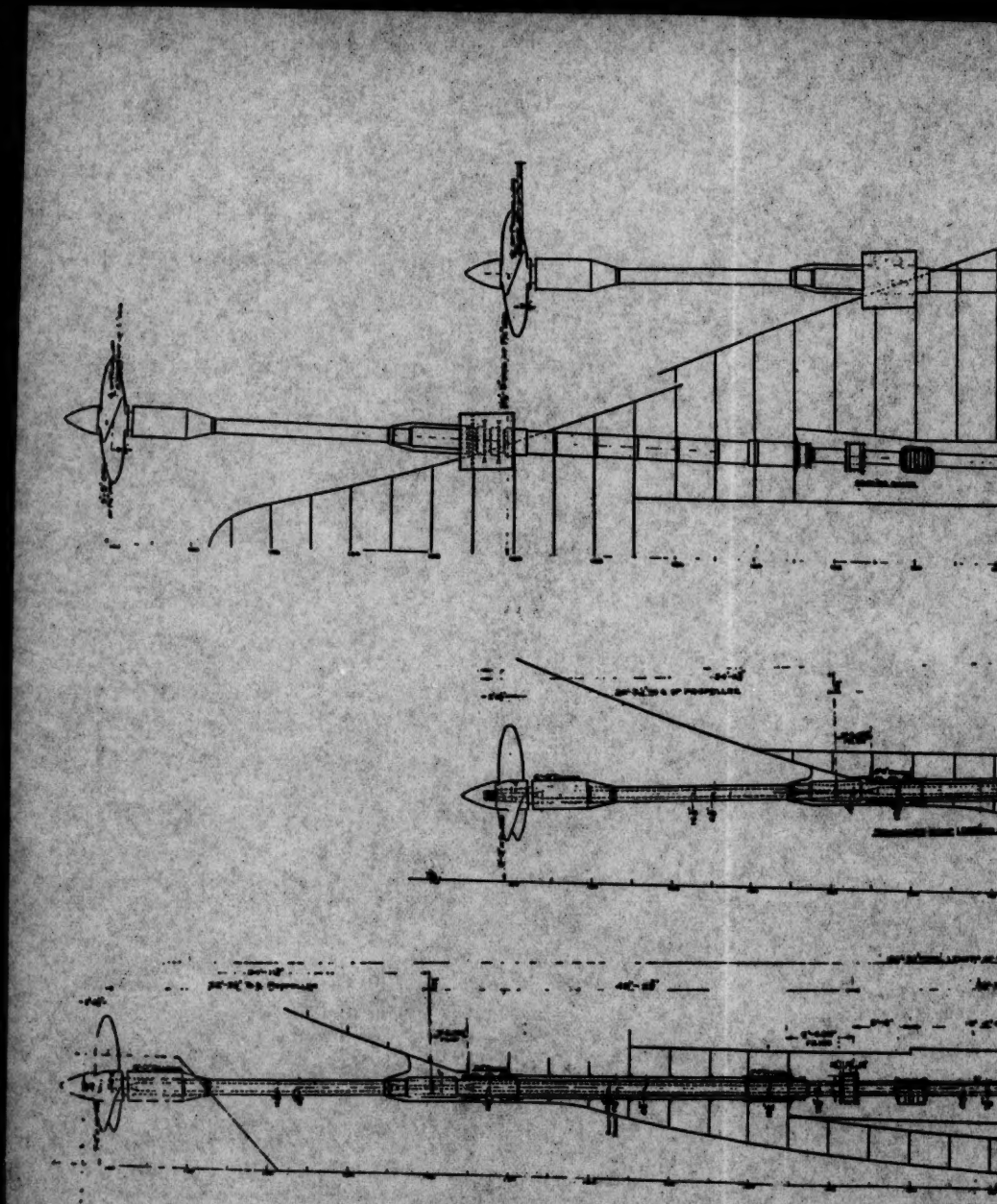


FIGURE 1.

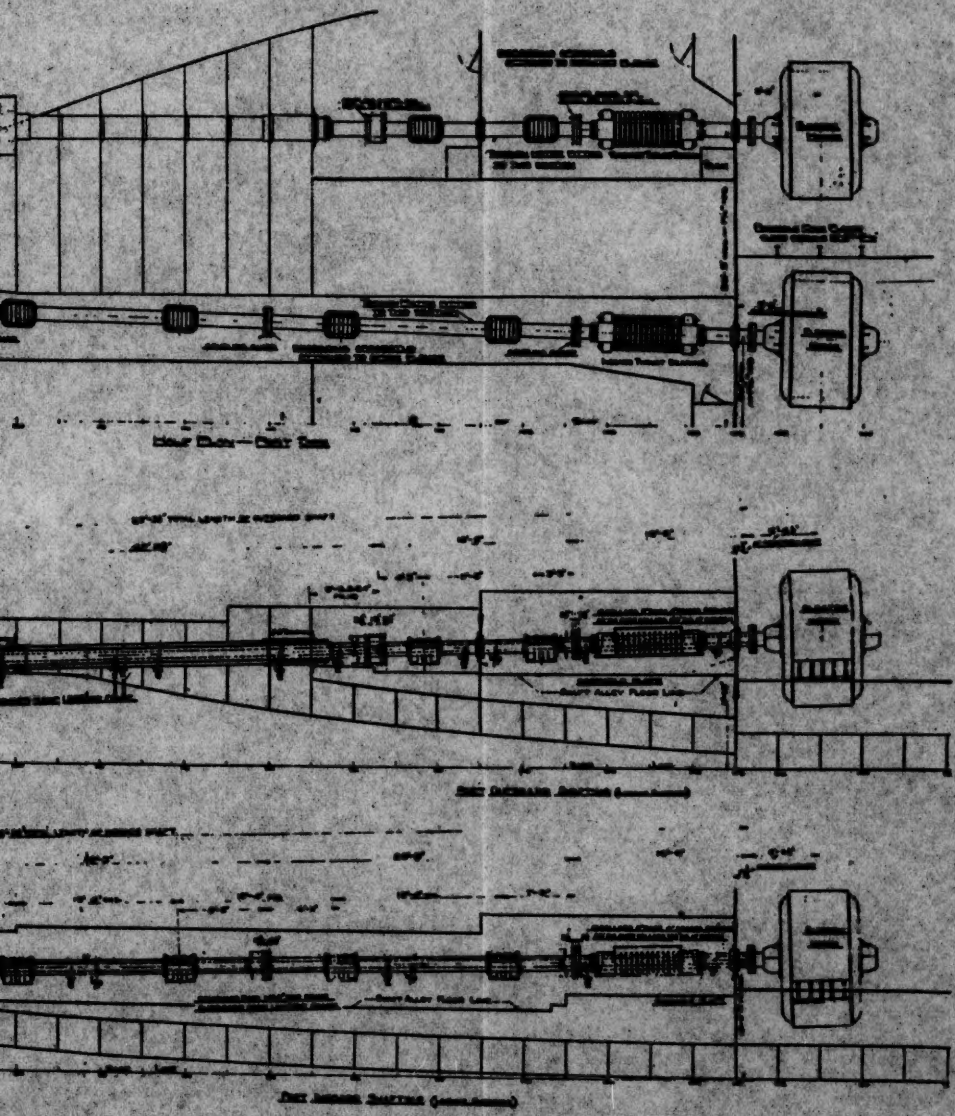
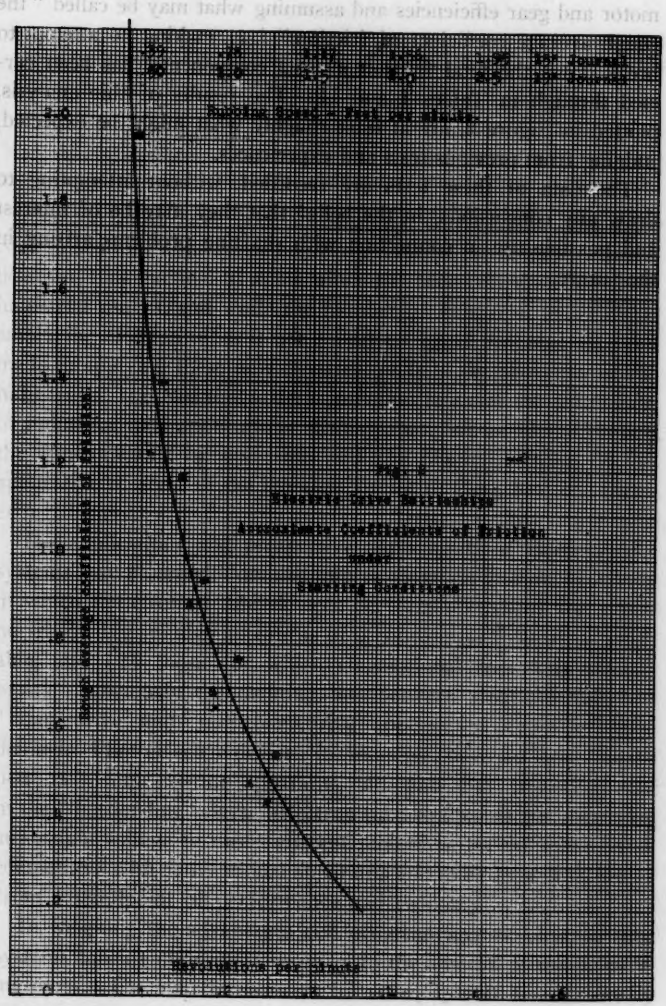


FIGURE 1.



An analysis of the data of Ship A making assumptions as to motor and gear efficiencies and assuming what may be called "the rough average coefficient of friction," *i. e.*, making no attempt to break down the total friction into its components, has been carried through in Tables I and II. The results of this analysis, plotted in Figure 2, are at least roughly what might be expected, judging from previous tests and experiences.

The data of these tests are recorded, without attempting to draw any conclusions, in the belief that they may be of interest and possible use in connection with shafting problems arising in the future.

ELECTRON TUBES IN INDUSTRY.*

By W. R. KING.†

GENERAL INTRODUCTION.

Electron tubes have been in everyday use in radio and other communication fields for a number of years. It is only recently, however, that the field of applications has been extended to include industrial usages, and while the number of industrial installations employing electron tubes is not enormous, great progress has been made in applying these new electrical tools to the problems of the industries. It is not the writer's intention to cover the entire field of industrial tube applications in this paper, but merely to present the fundamentals of operation and the practical aspect of the application of some of the more important of these new and interesting devices.

The applications and prospective applications of electron tube systems may be broadly divided into two general groups, (1) those in which the electron tube devices perform operations for which no reasonably suitable apparatus of a conventional nature is available, and (2) those for which conventional apparatus already exists. Obviously the dividing line between what we may call "competitive" and "non-competitive" applications cannot be clearly defined. Photo-electric devices for example, have no strict "competition" from existing apparatus, although they frequently fall in the "border-line" class. Electron tube equipment for supplying adjustable voltage to direct current motors is, on the other hand, competitive with conventional apparatus and must be so considered from a standpoint of performance and economy.

In weighing the advantages and disadvantages of electron tube systems consideration must be given to the absence of major moving parts. The maintenance cost for an equipment is undoubtedly

* A paper presented before the Midwinter Convention of the A. I. E. E., January, 1931.

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decreased if it contains no bearings to be oiled and no wearing parts to be frequently adjusted and occasionally replaced by skilled labor.

Another advantage that is generally important is that electron tube systems can respond to controlling functions of a very low energy level. In adapting electrical control to automatic machinery of various types the ability to secure control from small parts or from slight movements is often the difference between the failure and success of the machine.

The fragility of electron tubes has been a much discussed disadvantage in their application. It is obvious that the assemblage of glass and small metal parts must be handled and mounted with some care. For most applications, however, the fragility of the tubes is a psychological disadvantage rather than an actual one. The tubes are really more sturdy than they appear and it is felt that few potential applications of electron tubes will be found impractical because of the seemingly fragile nature of the tubes.

The question of tube life and tube replacement is largely one of economics. Tubes operated at rated values of current and voltage may be expected to have a certain average life. If they are operated somewhat under their rating this life expectation figure will be materially increased. By way of illustration, typical estimates of tube life at rated load run from 2000 to 10,000 hours. When used well below rated values, the tube life may be increased to as much as double its expected life at rated load. It is a matter of economics, then, to determine whether to use a certain tube at its rated load, or to use a larger and more expensive tube operating well under its rated load and thus secure a greatly increased life.

The actual replacement of tubes in an equipment does not require a skilled operator. Most of the tubes are provided with bases which fit into standard mountings so that changing tubes is almost as easy as replacing cartridge fuses.

THEORY AND CHARACTERISTICS OF PHOTO-ELECTRIC TUBE.

Fundamentally, the photo-electric tube is a two-element light sensitive device which depends for its operation on the emission of electrons from a light sensitive surface. There are other light

sensitive devices such as the selenium tube, which changes resistance upon the application of light, and the electrolytic cells, in which an electromotive force is created upon application of light, but I shall confine this discussion to a consideration of light sensitive devices in which electrons are liberated from a sensitized cathode and flow to a positively charged anode.

Sodium, potassium, rubidium, caesium, and other alkali metals have been used to form the sensitive cathode surface. Caesium is commonly used at present because its color sensitivity in the red end of the spectrum is higher than that of other alkalis.

There are at present two general types of photo-electric tubes, the gas filled tubes and the vacuum type tubes. In both types light liberates electrons from the sensitive cathode. If a source of potential is applied to the tube to make the cathode negative and the anode positive, the negatively charged electrons will be attracted to the anode. In the vacuum tubes this flow of electrons from cathode to anode constitutes the entire current passed by the tube. In the gas filled tubes, however, the maximum current which can flow is much greater than that represented by the number of electrons liberated from the cathode. The reason for this is that the electrons, in traveling from the cathode to the anode, collide with the atoms of the inert gas introduced in the tube and liberate from the atoms additional electrons which are also attracted to the anode. In going to the anode these electrons collide with other atoms releasing additional electrons, etc., etc. This phenomenon is called gas amplification and its use makes possible the construction of photo-electric tubes capable of passing approximately ten times the current per unit light flux that can be passed by the vacuum photo-electric tubes.

Because of the great chemical activity of the alkali metals it is necessary to use an inert gas in the gas-filled photo-electric tubes. Argon is most commonly used at present.

Both the vacuum and gas-filled photo-electric tubes are subject to variations in sensitivity (*i.e.*, anode current per unit light flux). These variations are greater for the gas-filled tubes than for the vacuum type.

The number of electrons emitted from the sensitive cathode (and therefore the current which the tube passes) is dependent

upon the amount of light on the cathode. For the vacuum photo-electric tube the relation between light flux and anode current (see Figure 1) is linear to a high degree of accuracy. For the gas filled tubes this relation has a slight curvature (Figure 1) but for most purposes may be considered substantially linear. This proportionality of current to light flux is the most important characteristic of the photo-electric tube and it is upon this characteristic that most of its applications are based.

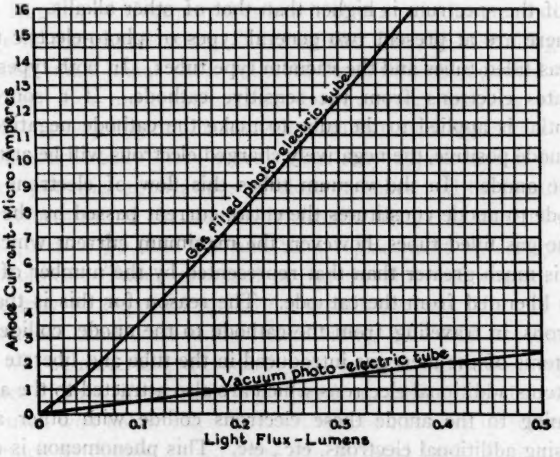

FIG. 1.—LIGHT FLUX—ANODE CURRENT CHARACTERISTIC FOR GAS FILLED AND VACUUM TYPE PHOTO-ELECTRIC TUBES.

The anode current is also affected by the applied voltage. The voltage determines the initial velocity of the electrons leaving the cathode. In the vacuum type tube only a few electrons reach the anode at low voltages. As the voltage is increased more and more electrons reach the anode until finally all the electrons emitted from the cathode reach the anode. Further increase in voltage cannot increase the current; therefore the tube is said to have reached saturation. In the case of the gas-filled tube, when the voltage is increased to the ionization potential of the gas, the gas ionizes and the anode current increases as the voltage is further

increased. The limit is reached when sufficient ions are produced to result in a glow discharge.

As mentioned in an earlier paragraph, caesium has a higher sensitivity in the red end of the spectrum than any of the other alkali metals. One type of caesium tube that has come into common use employs a very thin layer of caesium over a layer of caesium oxide which is deposited on silver. This tube has a very high total sensitivity compared to others and is characterized by a hump in the red end of its sensitivity curve as shown in Figure 2.

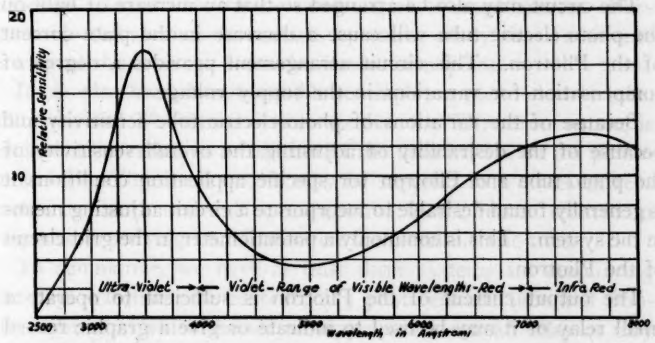

FIG. 2.—SPECTRAL SENSITIVITY CURVE FOR CAESIUM PHOTO-ELECTRIC TUBE.

AMPLIFICATION OF PHOTO-ELECTRIC CURRENTS.

To be readily useful, the minute photo-electric current (of the order of a few micro-ampères) must be amplified sufficiently to operate relays, ordinary recording and indicating instruments, or other devices. The most commonly used amplification systems employ a three element thermionic amplifier tube similar to the type which has become familiar as a radio amplifier. This type of tube will be referred to hereinafter as the Pliotron.* The circuit is so arranged that a change in the photo-electric tube current changes the grid voltage of the Pliotron. This results in a propor-

* General Electric Co. trade name for electrostatically controlled high vacuum discharge device.

tionate change of the Pliotron plate current which is of the order of milli-ampères and may be used to operate relays, etc. This type of circuit arrangement may be employed on alternating current or direct current. Because of the rectifying action of both the Pliotron and the photo-electric tube the alternating current circuit is active only when the respective anodes are positive. The resultant output is a half-wave pulsating direct current. The effective value of this current depends chiefly on the illumination on the photo-electric tube but is affected to an extent by variations in the supply voltage.

The circuit may also be arranged so that an increase of light on the photo-electric tube will cause a decrease in the plate current of the Pliotron. This circuit arrangement provides a degree of compensation for variations in the supply voltage.

Because of the variations of photo-electric tube sensitivity and because of the desirability of adjusting the overall sensitivity of the photo-tube and Pliotron for specific application conditions it is generally found desirable to incorporate a circuit adjusting means in the system. This is commonly a potentiometer in the grid circuit of the Pliotron.

The output current of the Pliotron is sufficient to operate a small relay or it may be used to indicate or give a graphic record of the amount of light on the photo-electric tube.

A relay capable of operating on the few milli-ampères output of the Pliotron, however, cannot control power circuits directly, nor even the operating coil circuits of medium size contactors or solenoids. It is necessary, therefore, to employ an additional small contactor before currents of the order of ampères can be controlled. In some applications this is perfectly satisfactory but frequently applications are encountered in which the speed of response required is too great for this concatenation of relays. In such cases it has sometimes been found advantageous to employ a Thyratron* in place of the relays. The operation of the Thyratron in this capacity will be discussed more thoroughly later. For the present we may consider it as an electronic device which has an anode current of the order of ampères which may be con-

* General Electric Co. trade name for electrostatically controlled arc discharge device.

trolled by certain functions of its grid voltage. In the system involving photo-electric tube, Pliotron, and Thyratron, the Thyratron grid is controlled by the output of the Pliotron in such a manner that when the illumination on the photo-electric tube reaches a predetermined value, the Thyratron suddenly conducts and will carry currents of several ampères—sufficient to operate directly power size contactor coils, solenoids, etc. When the light decreases below a certain value, the Thyratron stops conducting. In securing the amplification from micro-ampères to ampères by this system, the time lag is only a small fraction of that required by a series of relays to secure the same degree of amplification. Furthermore the absence of contacts operating many times a minute is a decided advantage from the service standpoint.

It has also been found possible to employ a photo-electric tube, Pliotron, and Thyratron system so that the Thyratron output is continuously varied as a function of the illumination on the photo-tube. The Thyratron output may be supplied to a direct current motor armature and full speed control of the motor secured in response to varying illumination on the photo-electric tube.

To summarize, we have at least three systems for amplifying the photo-electric tube current; (1) photo-electric tube and Pliotron system in which the output may operate a small relay or may be applied to an indicating or recording instrument to provide visual or graphic record of a light condition; (2) photo-electric tube, Pliotron, and Thyratron system in which the output is sufficient to operate directly solenoids, power contactors, etc., without the time lag encountered in using a series of relays to accomplish a like purpose; and (3) photo-electric tube, Pliotron, and Thyratron system in which the output is continuously variable in response to changing light functions, and is sufficient to operate small motors, etc.

COLOR ANALYSIS AND COLOR MATCHING.

A number of photo-electric equipments have been built for color analysis and color matching. I shall discuss briefly the recording color analyzer and one type of color comparator.

As its name implies the recording color analyzer is a photo-electric device which automatically draws for permanent record the

color curve of a sample. The device is constructed so that the light reflected from the surface of a solid material or the light transmitted by a transparent substance may be the basis of the final curve drawn. Light from a tungsten filament lamp passes into a dispersive system and emerges through a slit as monochromatic light. This light beam is then divided; half is focused on the sample, and half is passed through a shutter and focused on a flicker disc, which has on its surface a standard white pigment. The light from the sample is brought to a focus in the plane of the flicker disc and is passed into a photo-electric tube. As the flicker disc is revolved, the photo-electric tube views alternately the standard and the sample. A greater amount of light reflected from the standard than from the sample results in a pulsating photo-electric current which is amplified and used to control a motor operated shutter in the standard light path. This shutter will move until the light from the standard is equal to the light from the sample and therefore its position at each wave length indicates the amount of light required to equal that reflected by the sample. A pen on the recorder drum indicates this balance position. As the recorder drum revolves the wavelength of the light emerging from the dispersive system is varied through the visible spectrum. The curve obtained, then, indicates at each wavelength the balance point at which the light from the standard equals the light from the sample. The device is so constructed that the ordinates of the curve obtained become the reflection coefficients of the sample in terms of standard white. The device requires approximately four minutes to obtain a complete characteristic curve.

The use of this device opens a new field to those working with color in view of the fact that the curve obtained from a certain sample is absolute identification for its color. It is not inconceivable that in the future numbers will be applied to the many curves and the arbitrary names such as royal blue, cardinal red, canary yellow, etc., will be discarded for purposes of specification.

The color comparator is a much simpler device than the color analyzer. Its most important use is in matching colors. The device consists of a simple optical system and an amplifier. A milli-ammeter indicates the difference between light reflected from two specimens placed successively in the sample stand. A tri-

colored filter makes it possible to obtain comparisons in three parts of the spectrum in addition to white light. The accuracy seems to be as good as that of the eye for all samples and is better than that of the eye in the spectral regions where the eye is insensitive.

RECORDING OR INDICATING LIGHT CONDITIONS.

Applications requiring the continuous recording or indicating of amounts of visible energy on the photo-electric tube may be divided into three general classes; (1) light from a constant source passing through a substance of varying translucency or transparency to the photo-electric tube, (2) light from a constant source reflected into the photo-electric tube from a surface of varying reflecting power, (3) visible radiation from a varying source applied directly to the photo-electric tube.

The photo-electric tube and Pliotron system is employed in applications of this nature. In making such applications some inaccuracies are encountered due to voltage variations, changes in characteristics of photo-tubes, amplifying tubes, and light sources. Additional difficulties are occasionally encountered because of the entrance of undesirable dust or other matter into the path from the source of light to the photo-tube. Consideration must be given in each case to determine whether or not the accuracy secured will be acceptable, or if it is apparently not acceptable, whether or not the complication necessary to reduce the inaccuracies to acceptable values is warranted.

Photo-electric equipment of this nature has been used to make continuous records of smoke densities. In an application of this type a beam of light is transmitted through the duct carrying the smoke and onto the photo-electric tube. The variation in smoke density permits more or less light to fall on the photo-electric tube. When properly calibrated, then, the photo-electric current is a measure of the smoke density. A recording milli-ammeter measures the amplified photo-electric current and the resultant chart shows graphically the smoke conditions at all times.

Photo-electric equipments have been employed to provide records of daylight intensities. While this application does not serve the utilitarian purpose that the smoke density recorder does, it has provided some interesting data on daylight intensity variations.

Photo-electric tube and amplifying devices have been used for recording temperatures of hot bodies. At present, however, it is practically impossible for an electrical manufacturer to build a device which will be applicable to a number of different applications of this type. Each different application, then, will probably require some development, first to determine its feasibility, and second, to determine the best operating scheme.

Other applications have been proposed in which a continuous record would be made of light transmitted through liquids or reflected from a moving web of paper or material. Variations in the photo-electric current would ensue from changes in color, shade, density or some other characteristic of the material affecting its light transmitting or reflecting properties. While it is felt that no insurmountable difficulties would be encountered in making such applications, it is known that the difficulties in working out a specific case would be considerable and the writer does not know of any such actual installations at present.

RELAYING APPLICATIONS.

By far the greatest number of applications of photo-electric equipment which are operating at present are of the type in which an electric circuit is opened or closed in response to a certain change of illumination on the photo-electric tube.

In this manner street lights are being turned on in the evening and off in the morning in response to actual illumination requirements rather than according to a predetermined time schedule. The result is that on dark afternoons lights are turned on a little earlier than the time schedule because they are actually needed. On the other hand, a bright afternoon and evening keeps the lights off until they are required.

By similar devices electric signs are operated so that they are lighted when, because of low general illumination, their brilliance will attract attention, and are never lighted until illumination conditions are such that they will attract attention.

Room and factory lights can also be controlled in response to illumination requirements, with the result that sufficient illumination is maintained at a minimum cost for lighting energy.

Perhaps the simplest type of application of photo-electric equipment is that in which a beam of light falling on the photo-electric tube is intercepted by a practically opaque object and some electric circuit is closed or opened accordingly. By this means, for example, objects passing through the light beam may be accurately counted. The amplified photo-electric current operates a small relay which controls a magnetic counter. Or, if higher speed is required, the relay may be replaced by a Thyratron which will operate the counter directly. Photo-electric counters are being used commercially in counting automobiles, people, steel bars and billets on rolling mill tables, drops of oil in an automatic oiling machine, etc., etc., and are performing in such capacities in a thoroughly practical manner. Such a counting system offers distinct advantages in counting heavy objects which would soon destroy a mechanical counter, or small light objects which could not exert sufficient force to operate a mechanical counter. Often it is difficult or physically impossible to place a mechanical counter in such a position that it will be operated by the passing of objects. In using the photo-electric equipment, the devices may be placed at a considerable distance and the light beam alone projected across the path of the moving object. It is even possible to bend the light beam as desired to get it into some place difficult of accessibility. This can be readily accomplished by using clear fused quartz rods, through which light passes much like water through a pipe. The possibilities of photo-electric counting equipment have only been scratched and the writer believes that the next few years will find many industrial plants using photo-electric devices to secure an accurate count of their products.

This brings us to a consideration of photo-electric devices for limit switch operations. Their use in this capacity has made possible the automatic operation of machines in a manner which has not heretofore been practicable. Mechanical devices are not suited in some cases because of mechanical wear and tear, or because sufficient force is not available to operate them, or because of space limitations. It requires no additional force for a moving object to intercept a light beam; furthermore, the beam is in no way worn by the interception. In the manufacture of small cotton bags,

photo-electric relays are being employed to initiate operations on the bags when they are in the proper position. Photo-electric relays are being installed in ore bins to indicate when the ore has reached the proper level. A number of large pipe facing machines have been equipped and are in operation with photo-electric devices to stop the traversing motion and advance the cutting tool when the pipes reach the proper position. In a number of instances photo-electric relays have replaced mechanical limit switches on rolling mill tables.

Photo-electric devices can be made sensitive to smaller changes in illuminations than those characterized by the applications involving the interceptions of a light beam by an opaque object. For example, photo-electric equipment is being used to indicate the proper operation of a filter in a sugar refining process. A beam of light is passed through the solution and if the solution runs cloudy due to improper filter operation the decreased translucency causes the photo-electric device to operate an alarm. With proper illumination, black spots of sufficient size on paper or other material may be used to operate a photo-electric relay either by changing the amount of light transmitted through the paper to the phototube or by reflecting less light into it. Sorting devices can be made to operate from changes of reflected or transmitted light. The problem of sorting, however, becomes quite complicated if very fine discriminations are required. Furthermore, it is necessary to provide some means of passing the objects to be sorted in single file before the photo-electric tube at a rate which will be fast enough to perform the sorting on an economical basis.

The application of photo-electric devices to the simpler types of problems has been facilitated by the standardization of photo-electric equipments. Several electrical manufacturers have introduced complete photo-electric equipments including photo-electric tube, some type of amplifying arrangement, and a small relay. A device of this type which also includes a contactor is shown in Figure 3. The ability to procure such devices makes it no longer necessary for the plant engineer or production engineer to begin at the bottom and learn all about photo-electric tubes and amplifying systems when he sees the possibility of employing photo-electric devices to advantage.

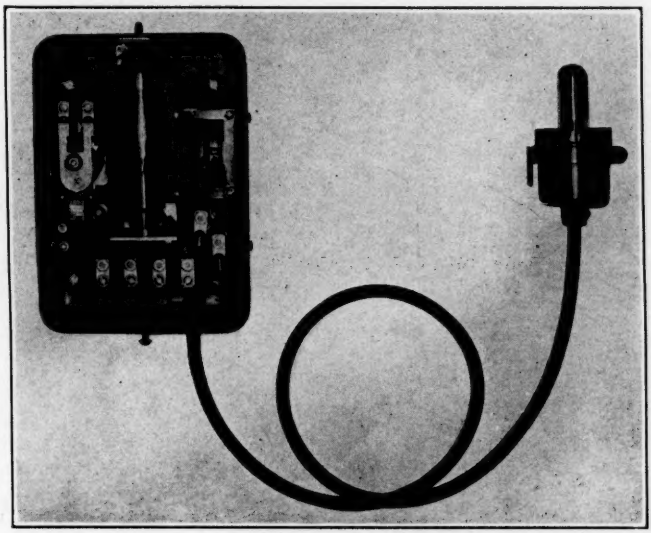

FIG. 3.—PHOTO-ELECTRIC RELAY.

PLIOTRON—GENERAL THEORY.

In our consideration of amplifying devices for the minute photo-electric currents we have mentioned the Pliotron. This tube has other applications in the industrial field and no general discussion of electron tubes would be complete without at least a brief résumé of its general theory and characteristics. The Pliotron is a three-element electronic device depending for its operation on the thermionic emission of electrons from a filament heated by an electric current. With a positive potential on the anode (or plate), the negatively charged electrons are attached to it. If a simple circuit of Pliotron, battery, and meter is arranged so that the positive battery terminal is connected through the meter to the anode, and the negative terminal to the filament, which is heated from another battery, the stream of electrons from the filament to the plate will complete the circuit and the meter will indicate a flow of current. If the battery is reversed the anode will be negative and no current will flow. It is apparent, therefore, that Pliotron is a rectifying device. If the battery is replaced by an alternating current source the current which is passed will be half wave pulsating direct current.

The grid is placed between the filament and the anode and controls the flow of electrons from the filament to the anode. If the grid is made negative it repels electrons itself and reduces the flow from filament to anode. It is possible to stop the electron flow completely by making the grid sufficiently negative. The relation that exists between grid voltage and plate current for different values of plate voltage is shown in Figure 4. This characteristic is utilized in almost every application of the Pliotron and it is this characteristic that has made the Pliotron and similar vacuum tubes almost invaluable as oscillators, amplifiers of weak signals, etc.

THE PLIOTRON AS AN AMPLIFYING DEVICE.

When the grid is maintained negative its current will be very small. Therefore the grid potential may be controlled with very little power. For this reason the tube may be used as an amplifier. Consider the amplification of photo-electric currents for

example. The currents are of the order of a few micro-ampères and the effective impedances may be many megohms. Although the energy level is very low, a slight change in photo-electric current causes a change of several volts in the high impedance circuit. This voltage change, applied to the Pliotron grid, is sufficient to change the anode current by several milli-ampères, enough for example, to operate a small relay.

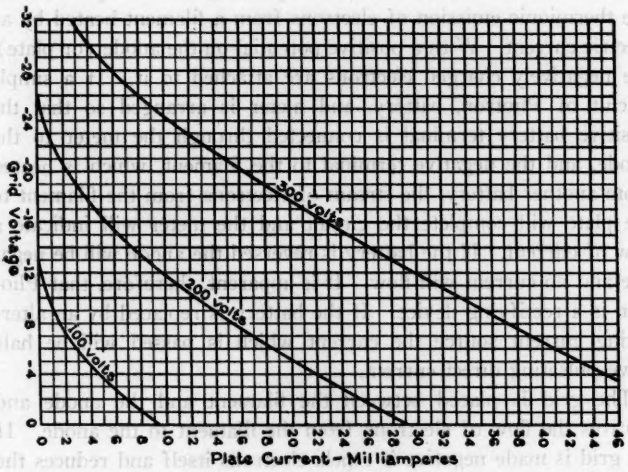

FIG. 4.—GRID VOLTAGE—PLATE CURRENT CHARACTERISTIC FOR A TYPICAL PLIOTRON.

This characteristic has been employed for several years in automatic train control. A small voltage is picked up from the tracks and amplified to operate signal devices in the engineer's cab.

The Pliotron may be used as a very sensitive relay to respond to the opening and closing of delicate contacts or to contact between an electrode and a conducting liquid (such as water).

THE PLIOTRON AS AN OSCILLATING DEVICE.

By a proper circuit arrangement in which the grid is inductively coupled to the plate circuit oscillations may be generated. Under certain conditions if the coupling between the plate coil and the grid coil is changed, as by placing an iron vane between

the coils the oscillations will be stopped. This characteristic of the oscillating circuit has been employed in the automatic leveling of elevators. An iron vane in the elevator hatchway passes between the plate and grid coil in an oscillating circuit on the car. When the iron vane is in the proper position the oscillations cease and a relay is closed, operating the control equipment which brings the elevator to a stop.

GENERAL THEORY AND CHARACTERISTICS OF THE THYRATRON.

Practically speaking, the Thyratron is a mercury arc or mercury vapor rectifier incorporating a control electrode or grid. We shall confine this discussion to a consideration of the hot cathode mercury vapor Thyratron. In this device a few drops of mercury have been introduced after exhaust. The current carrying capacity is due to electron emission from the hot cathode. The ionization of the mercury vapor, however, results in an approximately constant internal voltage drop of about fifteen volts.

The method of grid control is entirely different from that of the Pliotron. For a given plate voltage there is a particular grid voltage at which ionization will just occur, thus allowing the tube to pass current. If the grid potential is below this critical potential, *i.e.*, more negative, no discharge will occur and no current will pass. As soon as the grid potential is increased above the critical voltage, ionization occurs and the tube passes current, providing the anode is positive with respect to the cathode. Once the anode current is started, the grid has no appreciable effect on it. The grid cannot limit or stop the flow of current, but can regain control to keep it from starting again if the flow ceases long enough for the mercury vapor to de-ionize.

If an alternating current voltage is applied to the plate, the grid has an opportunity of regaining control once each cycle and can delay the start of the arc for as long a period during the cycle as the grid is sufficiently negative. Therefore, if the grid as well as the plate is supplied with an alternating current, the phase relation between the grid and plate voltage determines the point in the wave at which current begins to pass in each cycle, hence the average amount of current passing through the tube. Figure 5 shows this

relationship for one anode as the phase of the grid voltage is shifted from almost 180 degrees lagging to almost in phase with the anode voltage; the shaded portion indicates the passing of current.

We may consider then, that there are two methods of controlling the grid of a Thyratron supplied with alternating current; the voltage magnitude method and the phase shift method. The phase shift method makes it possible to vary the average current passed by the tube anywhere between zero and maximum while the voltage

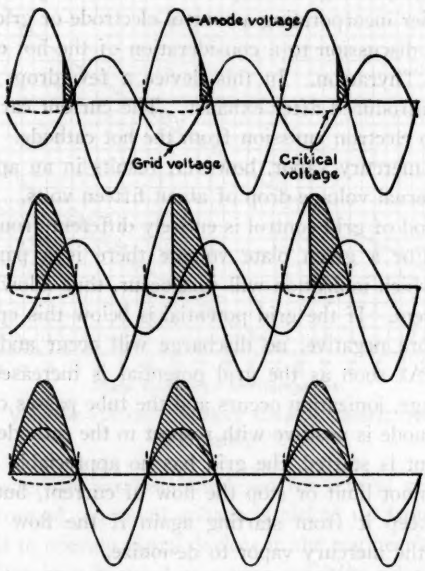

FIG. 5.—CONTROL OF THYRATRON BY SHIFTING PHASE OF GRID VOLTAGE.

magnitude method can be readily adapted only to control between full on and full off. The voltage magnitude method depends on the constancy of the critical grid voltage of the tube for its accuracy. The critical grid voltage will vary very slightly with tube temperature, age, etc.; therefore it is necessary that the change in applied grid voltage between "off" and "on" is greater than the

maximum variation in the critical grid voltage. In using the phase shift method of control for a relaying operation (*i.e.*, on and off) variations in critical grid voltage do not materially affect the accuracy.

Thyratrons are rated on an average and instantaneous current basis. For example, one size of Thyratron has a maximum average plate current of 2.5 ampères averaged over a period not to exceed fifteen seconds and a maximum instantaneous plate current of 10 ampères. This means that the tube will safely pass 10 ampères but that the duration of this current flow must not exceed a value which would make the average for fifteen seconds greater than 2.5 ampères. Thus if a tube is operating as a half-wave rectifier on a 60 cycle or 25 cycle system it could have an average current of 2.5 ampères by passing 5 ampères during each positive half cycle, *i.e.*, half the time. Similarly two such Thyratrons in a full wave rectifier system would have a maximum average direct current output of 5 ampères as each tube could pass 5 ampères half the time, *i.e.*, one tube on one half cycle, the other on the next. One larger tube has a maximum average current rating of 12.5 ampères. Two such tubes in a full wave rectifier circuit could provide 25 ampères direct current. It is extremely probable that Thyratrons of the future will be capable of passing current of the order of a hundred ampères or more.

Hot cathode Thyratrons require a brief time for heating of the cathode before power is applied. This is necessary to prevent damage to the cathode resulting in tube failure or a considerable decrease in tube life. In the case of the 12.5 ampère tube five minutes must be allowed, and for the 2.5 ampère tube one minute is sufficient. In applications requiring frequent starting and stopping, the cathodes are allowed to remain heated during stops and the time delay occurs only on the early morning starts.

The life of a Thyratron will depend on the service in which it is placed. Typical life estimates run from 2000 to 10,000 hours. If a very long life is required in a particular application it may be secured by using a tube whose current rating is higher than that actually required for the service. The question then is an economic consideration of first cost plus replacement costs of the small tube

against first cost of the larger tube, allowing due consideration to the value of the greater continuity of service secured with the larger tube.

THE THYRATRON AS A RELAYING DEVICE.

The operation of the Thyratron as a relaying device differs greatly from the operation of other relaying devices. It cannot be used as a direct current circuit interrupter. It may be used as a "valve" to "start" direct current in a circuit but cannot readily stop the current flow as long as the anode remains positive. It can be used, though, to start and stop a flow of current if alternating current is applied. The current which passes, however, is not alternating current but is half-wave pulsating direct current if one Thyratron is used. By using two tubes, so connected that one passes current in one direction on one half cycle and the other passes current in the opposite direction on the succeeding half cycle, it is possible to pass alternating current. This complication is not generally found to be warranted, however. The other major difference between a "Thyratron relay" and an ordinary relay is that the Thyratron has an approximately constant internal voltage drop of fifteen volts. This drop is substantially constant for all values of current within rating but varies slightly with ambient temperature, filament voltage, life of tubes, and between individual tubes.

The field of the Thyratron as a relaying device is chiefly in controlling solenoids, contactor coils, magnetic brakes and clutches, etc. Such devices may be wound to operate from the half-wave direct current voltage resulting from the application of commercial alternating current voltages to the Thyratron. Such a system involves no contacts and furthermore very high speed operation can be secured. The Thyratron grid circuit may be controlled by a change in either voltage or current directly; or by a change in reactance, capacitance, or resistance resulting in a change in voltage or a shift in phase of the grid voltage; or by the opening or closing of delicate contacts. In each case the change in the grid circuit must be sufficient to be independent of the slight variations in the critical grid voltage of the Thyratron.

For example, the amplified current of a photo-electric tube may be used to control the Thyratron. To accomplish this, a resistor is connected in the plate circuit of the Pliotron and the voltage drop across the resistor is used to control the grid voltage of the Thyratron and thus determine whether it shall conduct or not conduct. In this manner a change in illumination on a photo-electric tube may be employed to operate a solenoid or similar device without the aid of any contact making or moving part device whatever.

Similarly the change in reactance in a coil caused by moving an iron core in it may be used to shift the phase of the Thyratron grid voltage and control the operation of a magnetic clutch or brake.

One relaying device has been developed in which Thyratrons are employed to short circuit the high voltage secondary of a series transformer whose primary is connected in series with a resistance welding transformer. The change in the impedance of the primary of the series transformer as the Thyratrons are alternately permitted by their grids to pass current and not pass current, makes it possible to control at high rates of speed the intermittent flow of current to the welding machine without any mechanical wear and tear or burning of contact tips as experienced in mechanical interrupters and contactors.

THE THYRATRON AS A CONTROLLED RECTIFIER.

Although the Thyratron operates as a "controlled rectifier" in most applications this term will be used herein to refer to the Thyratron system in which alternating current is rectified to provide a pulsating direct current, the voltage of which may be varied smoothly and without "steps" by properly controlling the Thyratron grids.

The simplest system of this type is the single phase, full wave, grid-controlled rectifier, which will be discussed in detail. Figure 6 shows a schematic wiring diagram of such an arrangement. Neglecting the grid control feature for the moment we shall consider the operation of the circuit as a plain rectifier. When the anode of tube No. 1 is positive it will pass current from anode to cathode, through the load, and back to the neutral point of the

transformer. This current will continue to flow as long as the No. 1 anode remains positive. At the end of that half cycle the anode of tube No. 2 becomes positive and tube No. 2 conducts, the current passing from anode to cathode through the load and back to the neutral point of the transformer. Each tube conducts on alternate half-cycles, but permits current to pass through the load in the same direction in each half cycle. The voltage across the load is shown in Figure 7.

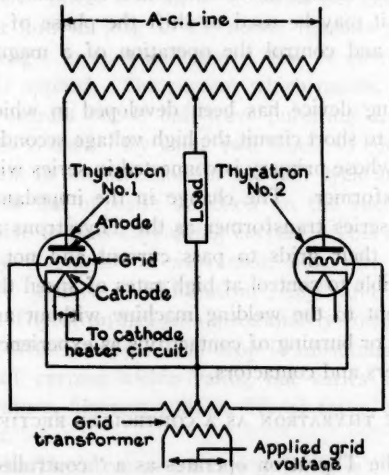

FIG. 6.—FULL WAVE GRID CONTROLLED RECTIFIER.

Now let us consider the effect of grid control upon such an arrangement with a resistance load. When the grid voltage is in phase with the anode voltage (*i.e.*, each grid in phase with its respective anode) the operation will be exactly the same as though the grids were not present because the grid of each tube will permit conduction as soon as the anode of that tube becomes positive. Furthermore, if the phase of the grid voltage is advanced to

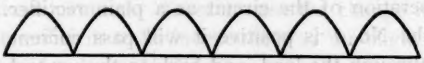

FIG. 7.—FULL WAVE RECTIFIER OUTPUT VOLTAGE WAVE FORM FOR RESISTANCE LOAD.

less than 180 degrees lead the operation will not be changed as the grid of each tube will be positive when its anode becomes positive, conduction will be permitted, and will continue for the remainder of that half-cycle despite the fact that the grid becomes negative meanwhile. If, however, the grid phase is retarded from the " in phase" position, *i.e.*, made to lag the anode voltage, the grids will not be positive when their respective anodes become positive and conduction in each half-cycle will not commence until the grids have become less negative than the critical grid voltage. As the phase of the grid voltage is made to lag the anode voltage more and more the point at which conduction begins comes later and later in each half cycle, conduction occurs for shorter and shorter periods and consequently the average voltage across the load is decreased. Finally, when the grids lag their anodes by 180 degrees, no conduction occurs because the grids are never positive when their respective anodes are positive. Figure 8 shows the relation between load voltage and grid phase angle lag. The inductance in the supply transformer accounts for the slight deviation of the practical curve from the theoretical.

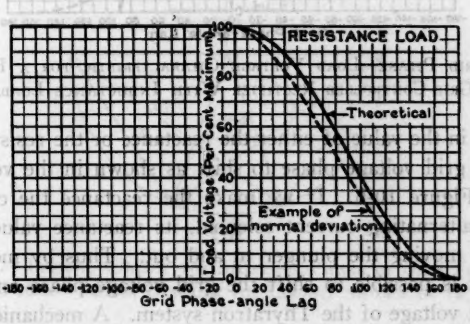

FIG. 8.—GRID PHASE—LOAD VOLTAGE CHARACTERISTIC FOR A FULL WAVE GRID CONTROLLED RECTIFIER SYSTEM WITH RESISTANCE LOAD.

In the case of an inductance load the operation is somewhat different because the energy storage in the inductance tends to make the flow of plate current hold over into the negative half cycle. A thorough discussion of the phenomena involved in this type of operation would be somewhat complex and probably beyond the

scope of this paper. Figure 9, however, shows the theoretical relation between load voltage and grid phase angle lag for a theoretical pure inductance, and also an example of typical deviation caused by the resistance present in a practical inductance.

To make the system serve a useful purpose it is necessary to devise means for shifting the phase of the grid voltage of the Thyratrons in response to electrical functions or mechanical movements. One very simple method of securing such a phase shift is to set up a reactance-resistance bridge as shown in Figure 10-a.

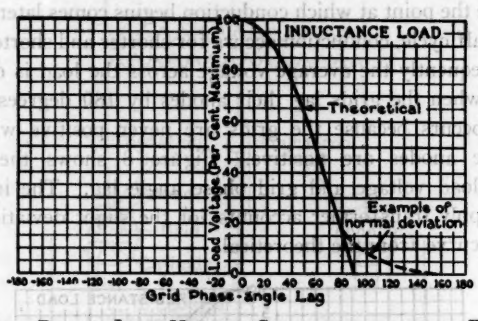

FIG. 9.—GRID PHASE—LOAD VOLTAGE CHARACTERISTIC FOR A FULL-WAVE GRID-CONTROLLED RECTIFIER WITH INDUCTANCE LOAD.

A change in the value of either the reactance or the resistance will cause the grid voltage phase to shift as shown in the vector diagram in Figure 10-b. If we make the reactance the coil of an ordinary alternating current solenoid, its reactance value may be varied by moving the plunger in and out. Thus by moving the plunger it is possible to shift the grid voltage phase and change the output voltage of the Thyratron system. A mechanical movement of an inch and a half can control the voltage from zero to maximum.

The alternating current coil of a small saturable core reactor may be connected in a circuit arrangement in such a manner that variation of the direct current through the direct current coil of the reactor will shift the phase of the grid voltage. In this manner variations in a direct current of a few milli-ampères may

control the output voltage of the Thyratron from zero to maximum.

A very small induction voltage regulator may be used in a circuit combination in which rotation of the regulator rotor causes the grid voltage to shift in phase and, consequently, the Thyratron output voltage to vary.

It is apparent, then, that there are a number of ways in which the phase shift of the grid voltage may be accomplished in response to changes in voltage or current, or in accordance with rotary or linear mechanical motions. Undoubtedly many new schemes will be devised to fit particular applications as the art progresses.

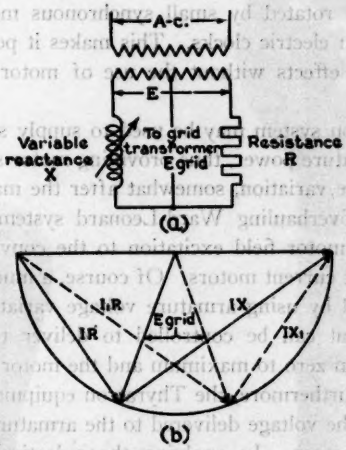

FIG. 10-a.—TYPICAL CIRCUIT FOR SHIFTING PHASE OF GRID VOLTAGE.
FIG. 10-b.—VECTOR DIAGRAM FOR CIRCUIT SHOWN IN (a)

The first important commercial installation of Thyratron control was made in the Chicago Civic Opera House. In this installation full wave grid-controlled rectifiers are employed to provide adjustable voltage direct current for saturable core reactors controlling the lighting effects for the stage and auditorium. The grids are controlled by means of small rotary regulator units. As the regulator unit is rotated the phase of the grid voltage is

shifted, the Thyratron output voltage changes, varying the degree of saturation in the saturable core reactors. The reactance of the alternating current coil of the reactor changes accordingly, permitting more or less current to flow through the lighting circuit, thus controlling the intensity of the lights. Thyratron control is also employed in this installation to control the speed of a direct current motor by which it is possible, through a system of Selsyn* devices, to rotate all of the individual regulators for the various lighting circuits simultaneously, and thus control all of the lighting circuits from the rotation of one regulator.

Similar systems have been applied to other lighting control systems. The grid controlling regulators are so small that they may be continuously rotated by small synchronous motors similar to the kind used in electric clocks. This makes it possible to secure cyclic dimming effects without the use of motor operated rheostats.

The Thyratron system may be used to supply small direct current motor armature power, thus providing motor speed control by armature voltage variation, somewhat after the manner of a non-reversing, non-overhauling Ward-Leonard system; or it may be used to supply motor field excitation to the conventional adjustable speed direct current motors. Of course, a much greater speed range is secured by using armature voltage variation. The Thyratron equipment can be controlled to deliver to the armature any voltage from zero to maximum and the motor speed will vary accordingly. Furthermore, the Thyratron equipment may be controlled to vary the voltage delivered to the armature smoothly, *i.e.*, in infinitesimal steps. In applying the pulsating direct current voltage to the motor armature, the ripple must be limited to secure good commutation. This is accomplished by connecting a suitable smoothing reactor in the direct current circuit. As in other applications, the energy required to control the Thyratron grids is very small.

The speed range which may be secured by using the Thyratron equipment to supply field excitation is limited by the motor itself. The application of this system generally requires that both alternating current and direct current power be available, since the Thy-

* General Electric Co. trade name for self-synchronous motion transmitting apparatus.

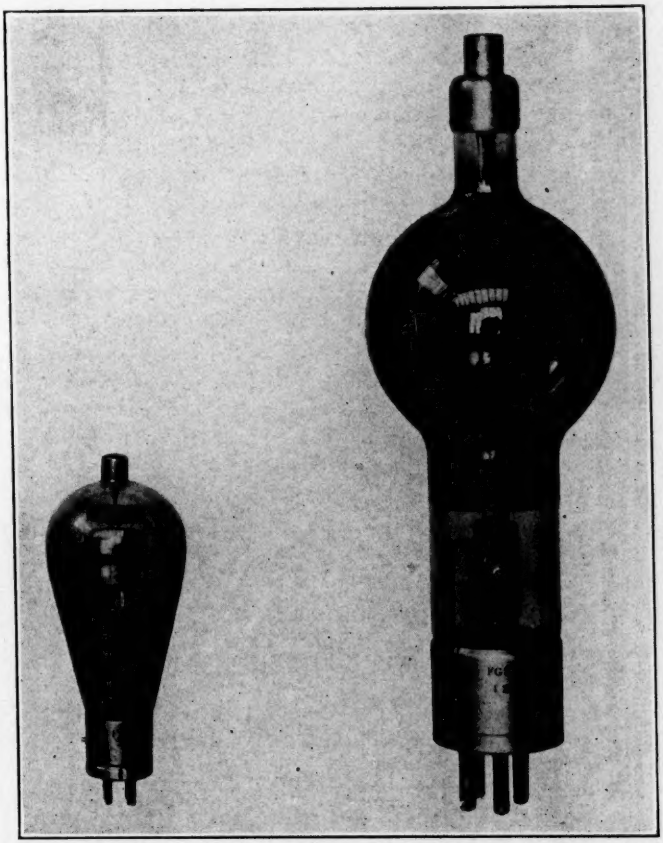

FIG. 11.—SHOWING THE RELATIVE SIZE OF A 2.5 AMPERE THYRATRON AND A 12.5 AMPERE THYRATRON.

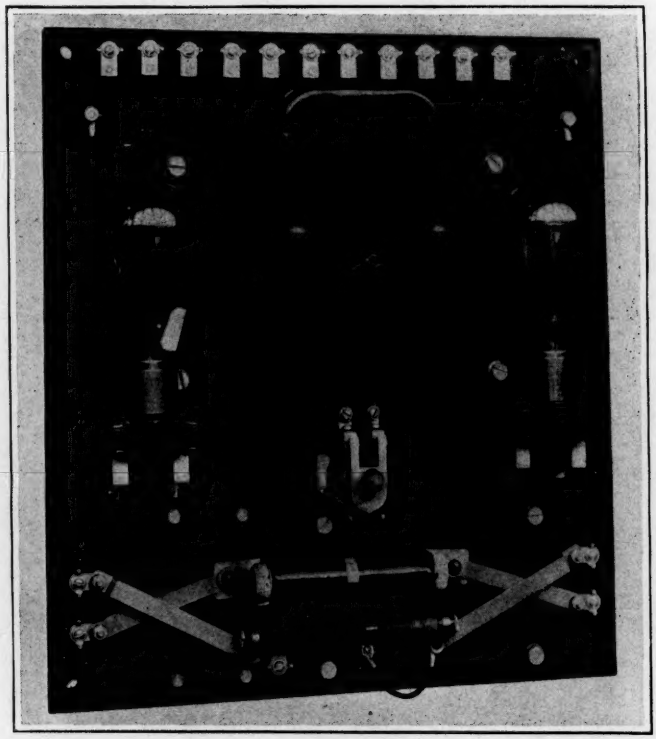

FIG. 12.—THYRATRON PANEL FOR SUPPLYING VARIABLE VOLTAGE D.C. TO A 1 H.P. MOTOR.

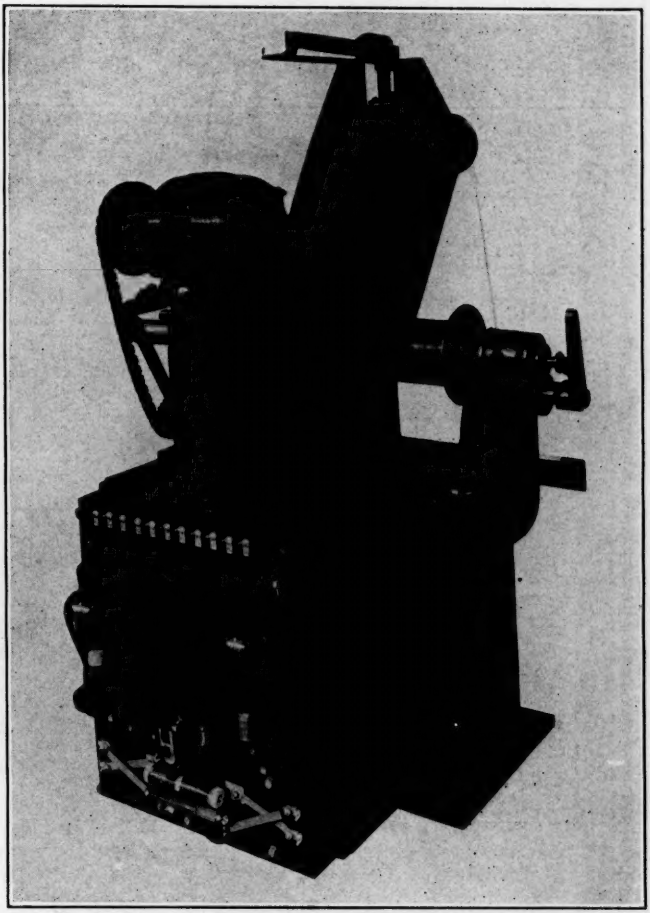

FIG. 13.—WIRE DRAWING WINDER EQUIPPED WITH THYRATRON CONTROL.

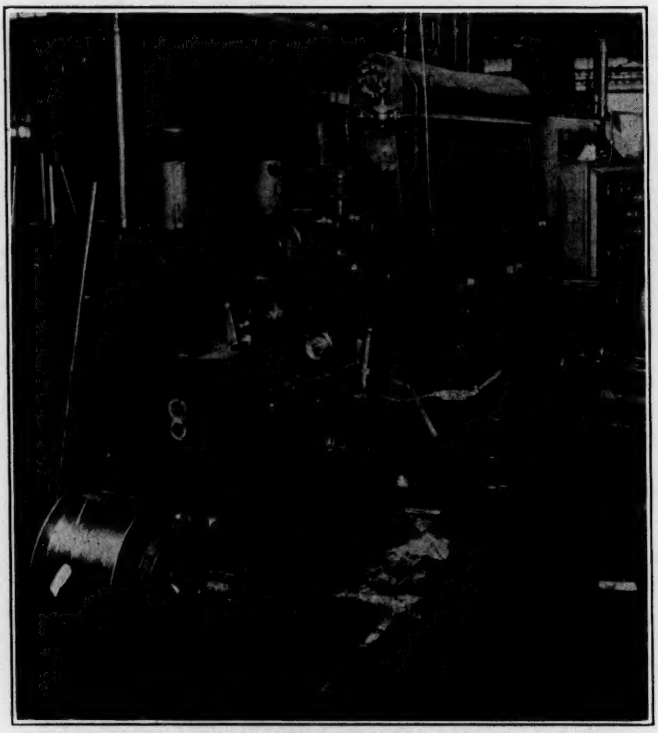

FIG. 14.—WIRE DRAWING WINDER SHOWING D.C. MOTOR SUPPLIED WITH VARIABLE VOLTAGE FROM THYRATRON PANEL AND TENSION REGULATING DEVICE CONTROLLING SMALL REACTOR IN GRID CIRCUIT OF THYRATRONS.

ratron equipment operates from alternating current and direct current must be supplied for the motor armature. The Thyratron equipment in this case merely provides a direct current source of excitation with unusual control features for conventional adjustable speed motors. The occasion that would warrant the installation of a motor generator or rectifier to supply armature power, in addition to the Thyratron equipment to supply controlled excitation, would be unsual, although cases justifying such an arrangement may arise.

With the Thyratrons at present available for industrial use it is possible to supply armature power for motors up to 5 horsepower, 230 volts, and field excitation up to 5 kilowatts, 230 volts. Figure 11 shows a Thyratron panel for supplying armature power to a 1 horsepower, 230 volt motor. Each of the Thyratrons on this panel has an average current rating of 2.5 ampères so that the total average output may be up to 5 ampères, which is sufficient for a 1 horsepower, 230 volt motor. Figure 12 shows a 2.5 ampère tube with a 12.5 ampère tube. A panel similar to that shown in Figure 11 but employing two of the larger tubes is capable of supplying up to 25 ampères direct current which is sufficient for a 5 horsepower, 230 volt motor. Power for motors larger than 5 horsepower would have to be taken from a three-phase distribution and a three-phase grid-controlled rectifier circuit would have to be used.

An installation of Thyratron motor control is being employed to maintain constant tension on a wire drawing winder. To successfully wind fine wire after its final drawing it has been found necessary to maintain a practically constant tension in the wire as the reel diameter increases and as the speed of the drawing machine varies. The Thyratron equipment has been found to meet these requirements admirably. In this installation (Figures 13 and 14) a solenoid armature is attached to a floating pulley and moves up or down as the tension of the wire under the pulley increases or decreases. The winder motor speed is accordingly decreased or increased by the Thyratron control which supplies its armature power. As this operation is continuous and the response to a change in tension is almost instantaneous, a practically constant tension results.

Another installation of Thyratron motor control is being made for controlling the speed of a motor driving a reeling machine for rubberized belting. Here again the control is to function in response to change of tension in the belting as the reel diameter increases.

Many additional possibilities are open to consideration from an engineering and economic viewpoint. The Thyratron should be given due consideration wherever relatively small powers of adjustable voltage direct current are required and should be given special consideration when automatic control of such voltage is desired in response to mechanical movements or electrical functions.

NOTES.

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The Western Society of Engineers, February, 1931.

CASE-HARDENING WITH AMMONIA GAS.
The Tech Engineering News, April, 1931.

CORROSION AND HEAT RESISTING STEELS.
The Tech Engineering News, April, 1931.

TRENDS IN STEAM-TURBINE DEVELOPMENT.
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THE USE OF PURE IRON ELECTRODES FOR WELDING CAST IRON.
Mechanical World and Engineering Record, March 6, 1931.

CREEP OF METALS AT ELEVATED TEMPERATURES.
Mechanical Engineering, March, 1931.

THE HYDROGENATION OF PETROLEUM.
The Petroleum Times, March 14, 21, 1931.

AXIAL VIBRATION OF ROTATING STEAM TURBINE DISC WHEELS.

R. H. COLLINGHAM, M. INST. C. E., M. I. MECH. E.

The designing of turbine disc wheels to resist centrifugal, temperature and boundary loads, and at the same time to be free from axial vibration, entails technical investigations of a very elaborate nature. As regards the calculations to take care of centrifugal, temperature and boundary loads, these are carried out along generally accepted methods, and that a wheel will be satisfactory to take care of these conditions by calculation alone can be assumed with safety. On the other hand, the calculations required to ensure safety from axial vibration are not developed to the degree that freedom from axial vibration can be definitely predicted.

Now, axial vibration of a turbine disc wheel responsible for serious failures, takes the form of a wave train travelling round in the turbine disc against the direction of rotation. Any one of the pulsating forces existing in a steam turbine and acting on any of the discs may coincide in its frequency with that of a certain natural mode of vibration of the latter, and thus cause the phenomenon of resonance even for impulses of very small magnitude. Under such circumstances, the amplitude of the disc wheel vibration may build up to a dangerous limit.

When the natural period of wheel vibration is the same as that of normal speed of rotation of the turbine, a very small lateral impulse from the steam at one point in excess of that at other points is accumulated to a large force where energy is stored in the vibration of a given wheel element. As a result, the deflection produced from a given force increases gradually with a lapse of time, until after several hundred rotations the swing of the wheel has a large amplitude and energy is accumulated from several hundred impulses. The vibrating disc wheels running with comparatively small clearance between the diaphragms will ultimately deflect sufficiently to rub on the diaphragms, and, if the turbine is not shut down, serious damage to the wheels and stationary portions of the turbine may occur.

It has already been mentioned that the type of vibration responsible for practically all serious wheel troubles consists of a train of backward travelling waves. When the backward speed of the travelling waves in the wheel exactly equals the forward speed of rotation, the result is waves which are stationary in space. If it is found that, when a turbine disc wheel is running at normal speed, the backward speed of the travelling waves is such that the resultant is stationary in space, it is possible for a wave train of large amplitude to develop which may cause serious trouble unless checked. The particular speeds of a turbine disc wheel at which the backward speed in the wheel exactly equals the forward speed of rotation, is called the "wheel critical speed." Every turbine wheel has a series of particular speeds for which the backward speeds of wave trains of four, six, eight, and ten nodes, &c., corresponding to two, three, four, and five nodal diameters, &c., are equal to the forward speed of the wheel.

Returning to the question of the designer's ability to calculate a turbine disc wheel to be free from critical nodal vibration, as already stated above, we are not as yet able definitely to predict this with certainty by mathematics only for the following reasons:—Very important disturbing influences are found to exist between theory and actual facts. Among these departures from theoretical assumptions which account for variation between test and calculation in ordinary cases are the following:—

(1) Difference between assumed wheel shape and actual wheel shape. This difference may be between the actual wheel as manufactured and the drawing, or between the drawing and the shape assumed to represent it in the calculation.

(2) Manner of support; that is, whether the disc is continuous at the center or is off the shaft or shrunk on the shaft, and the degree of tightness of the fit, &c.

(3) The tightness of dovetail connection at the bucket roots, a condition affected by the speed of rotation.

(4) Condition of internal stress throughout the web of the disc. This is greatly affected by differences of temperature between the center and circumference of the wheel.

From the above it will be seen how difficult, if not impossible, it is to calculate the critical speed of nodal vibration of a wheel disc by theoretical considerations alone. There are designers who argue their ability to calculate discs to be safe from critical nodal vibration along the following lines:—

The frequency of a given type of vibration is determined by two factors (a) the stiffness and (b) the mass of the vibrating body. The stiffer the body, the faster it vibrates, and the more massive it is the slower it will vibrate. Now, centrifugal force has no effect on the mass of the wheel, but it has a powerful stiffening effect. This force acting radially outward around the edge of the wheel stiffens it and raises its vibration frequency. Therefore it is safer to infer and can be proved experimentally that centrifugal forces raise the natural vibration frequencies of a turbine disc wheel. If therefore the turbine disc wheels are designed of such a massive section that the stationary frequency of vibration for two, four, six, eight, &c., nodes, or, in other words, one, two, three, four, &c., nodal diameters is greater than the frequency of the impulses likely to build up nodal vibration in the discs, then disc wheels free from critical nodal speeds at the normal operating speed of the unit will be obtained.

For a turbine running at 1500 R.P.M., the number of impulses will be fifty per second for two diameters or four nodes, seventy-five per second for three diameters or six nodes, one hundred per second for four diameters or eight nodes, &c. For a turbine running at 3000 R.P.M. the number of impulses will be 100 per second for two diameters or four nodes, 150 per second for three diameters or six nodes, 200 per second for four diameters or eight nodes. This basis of design, however, is not economical from the point of view of manufacturing cost, dimensions of unit, &c. It results in disc wheels being designed of unnecessarily heavy section in order to ensure the conditions being met, it necessitates increased shaft dimensions, and it probably requires a greater overall length of the set in order to accommodate the unnecessarily stiff section of wheel requisite to meet the conditions.

The policy enunciated above assumes that the only practical way of taking care of disc vibration is to provide unnecessarily stiff discs. However, the brilliant series of investigations carried out by the late Mr. Wilfred Campbell on behalf of the General Electric Company of America, has made it possible for designers to produce turbine discs of comparatively light section which can be safely operated when the natural frequency of the disc wheel lies below the frequency of impulses tending to produce vibration. The late Mr. Wilfred Campbell was a Manchester man, and an engineer of outstanding ability. He served his apprenticeship with the Lancashire and Yorkshire Railway, and afterwards, emigrating to America, he joined the turbine design staff of the General Electric Company, at Schenectady.

By means of what is known as the wheel testing machine Campbell demonstrated that it is possible exactly to predict the speed at which critical nodal vibration will occur, and if this critical speed lies within certan limits which have been proved to give safe operation, then by tuning—that is to say, by removing metal from the turbine disc until the critical speed lies outside the range for safe operation—entirely satisfactory operation can be obtained.

There is another aspect of the question which requires to be borne in mind in assuming safety from operating troubles by designing turbine wheel discs so stiff that the natural frequency of the disc is greater than the frequency of the impulses likely to build up nodal vibration at the normal running speed of the turbine. The effect of temperature conditions in the discs is to lower natural frequency by an appreciable amount. The magnitude of this lowering of natural frequency is one which it is very difficult to estimate by calculation, and it may therefore well be that although static tests of natural frequency of the discs for different number of nodes may appear to lie well above the frequency of the impulses at normal running speed likely to build up critical nodal vibrations in the disc, nevertheless the effect of temperature conditions may be such that the lowering of the natural frequency of a certain definite number of nodes coincides with the impulses at normal running speed likely to build up critical nodal vibration.

In this event at some definite value of load and temperature conditions in the turbine trouble will occur, due to the wheels rubbing the diaphragms with injurious results unless rapidly checked. Where the bladed disc wheels are tested in a wheel vibration testing machine the discs are heated up considerably owing to rotation losses although steam for cooling purposes is circulated through the machine, and therefore the effect of temperature on the disc is approached by the tests carried out in the wheel vibration testing machine.

When static vibration tests alone are relied upon it will therefore be seen that it is difficult to be certain that the turbine disc wheels will be free from critical nodal vibrations at normal running speeds of the turbine. Moreover, as stated previously, this method of design results in unnecessarily heavy discs, shafts, &c., in order to be certain beyond all question that natural frequencies of the discs are not going to coincide at some number of nodes or of nodal diameters with the frequency of the impulses at normal running speed. The methods of tests for both static and dynamic conditions furnish the means to avoid with certainty such vibrations.

Recently the British Thomson-Houston Company, Ltd., of Rugby, built a wheel vibration testing machine in which complete static and dynamic tests on turbine disc wheels can be carried out. This apparatus was built on account of trouble which was experienced with the 32,000-Kw. turbo-alternators at the Kearsley power station of the Lancashire Electric Power Company. These turbines are of the two-cylinder type running at 1500 R.P.M. and having six stages in the high-pressure cylinder and eleven stages in the low-pressure cylinder. They operate on steam at 300 pounds per square inch gauge, 253 degrees F. superheat, and are designed for a vacuum of 28.83 inches of mercury at 32,000 Kw. load. The profile of the discs used in these machines was identical with other discs which had operated successfully for a period of twelve years. The only difference lay in the loading conditions of the wheels and the steam density in the stages of the low-pressure casing; the steam load and density being generally higher in the case of the Kearsley units.

It was found on opening up these units for inspection that there were definite indications of four-nodal rubbing in the low-pressure casing. Now, it can be proved for the case of a particle with an elastic support that

$$f_r = \sqrt{f_s^2 + BN_s^2}$$

where f_r=the frequency of the particle due to the combined effects of stiffness and rotation,

f_s=natural frequency of vibration,

N_s=speed in revolutions per second,

B=arbitrary coefficient hereinafter termed the "speed coefficient."

Campbell, on behalf of the General Electric Company, of Schenectady, justified this formula many hundreds of times for use with a complete turbine bucket wheel by actual measurement. Stodola also arrived at the same conclusion on theoretical grounds. Now, it is an easy matter with suitable precautions to ascertain f_s the natural frequency of vibration of a turbine disc wheel by vibrating the wheel by means of an A. C. magnet. To be certain of the value of f_r—the frequency due to the combined effect of stiffness and rotation—is a very different matter because of the uncertainty of the value of the speed coefficient B. The value of the speed coefficient is influenced, as already stated, by the shape of the wheel disc, by the degree of tightness of fit, manner of support on the shaft, tightness of dovetail connection at the bucket roots, condition of internal stress throughout the web of the disc, which is in turn greatly affected by differences of temperature between the center and circumference of the wheel. The ascertaining of the value of the speed coefficient B is therefore a matter of vital importance in order that the critical nodal speeds of turbine disc wheels of new design may be predicted with a reasonable degree of certainty.

It was on account of the uncertainty existing with regard to the value of the speed coefficient in the case of the Kearsley wheel that the British Thomson-Houston Company decided to build the apparatus which would put it in a position to run any wheel on which it was considered desirable to obtain definite data as to critical nodal speeds, speed coefficient, tangential bucket vibration, &c. Referring to Figure 1, it will be seen that the wheel testing machine consists of a case within which the wheel to be tested is rotated. This casing—see the cross-section below—is made of forge steel for protection in the case of accident to the wheel under test, and is split on the horizontal center line. It forms a steam chamber in which the test wheel is mounted on a shaft alongside a very stiff disc or wheel which is termed the coil-carrying wheel. The shaft carrying the two wheels may be rotated at any required speed by means of an external steam turbine, clearly seen on the right-hand side of Figure 1. Two pipes are connected to the bottom half of the fabricated steel casing. One of these pipes supplies steam to the casing when necessary, whilst another pipe is utilized to convey the exhaust steam to the vacuum pump and condenser. The rotating shaft is sealed through the fabricated steel casing by means of carbon packed glands. An absolute pressure of about 4 pounds per square inch is maintained in the casing during standard tests.

The purpose of circulating the steam in the wheel chamber during the test is to keep the wheel relatively cool. If turbine wheels are rotated at high speed while surrounded by air at atmospheric pressure, so much heat is generated by the windage that the temperature of the wheels becomes unduly high. By circulating steam through the casing to the vacuum pump and condenser, the heat energy generated by rotation of the wheel is removed, and the temperature of the wheel is maintained at the desired

value. Figure 2 shows a view of the machine with the top-half casing removed and the two wheels mounted on the shaft and dropped into the case. The right-hand wheel is the coil-carrying wheel and the left-hand wheel is the wheel under test.

It will be noted that the shaft is provided at the left-hand side and close to the pedestal cap with three slip rings and brushes in contact with them. The use of these parts will be stated later.

It will also be noted on the left-hand side of Figures 1 and 2 that an alternator is provided, which is driven at synchronous speed through a light flexible shaft from the main testing spindle. In order to observe or record wave motions or vibrations, which may occur in the wheel under test, a standard oscillograph is used, together with two sets of exploring coils suitably arranged within the wheel testing machine. One set is stationary and the other rotates with the wheel being tested. The stationary coil transmits to the oscillograph, which records them, electrical indications of the movement of the wheel rim towards and away from the exploring coil as the wheel passes by the coil. The movable coil, which rotates with the wheel, on the other hand, records only the lateral motion of one given point in the wheel circumference. The records from these two coils disclose the nature of the wave phenomena developed in the wheel.

The exploring coils within the casing of the wheel testing machine are made steamproof by complete enclosure in a metal casing. Metal-cased wire is used for the electrical connections to the coils. The rotating coils are carried in a tubular member, fastened on the periphery of the relatively stiff coil-carrying wheel, always used in testing, the vibration characteristics of which are so well known as not to be confused with those of the wheel under test. The tubular member is held parallel to the shaft and is adjusted in order to obtain the desired air gap between the coil and the test wheel. The metal-cased conductor from this coil is carried down the side of the coil-carrying wheel, brought out through the end of the hollow shaft, and connected to a collector ring. Another coil is placed 180 degrees away. This is used as a reserve and it serves also to maintain balance. The fixed exploring coil, already referred to, is supported within the casing adjacent to the wheel rim, the metal-cased wire connection from this coil being brought outside the casing, where electrical connection is made with the oscillograph.

Figure 3 shows a sectional assembly of the wheel vibration testing machine. A is the fabricated steel case, B the shaft on which are pressed the coil-carrying wheel (C), and the wheel to be tested, D E is the rotating coil holder, which is stayed by brackets F. The two rotating coils are connected by copper sheathed leads to the slip rings G. Three slip rings are shown, one for each rotating coil, and one for the common return. H are the carbon packing casings to seal the shaft for vacuum; I is the alternator driven at synchronous speed by the wheel testing machine shaft by the coupling J. The shaft B is, in turn, rotated at any required speed by the torque shaft K from driving turbine shaft L. M is one of the stationary coil holders; N is an A. C. magnet, which is used for the purpose of taking the stationary nodal frequency tests. It is also used when energized with D. C. to put a pull on one side of the turbine disc wheel in order to pull out the wave in the disc if there is difficulty in getting the wave to build up.

The electrical connections of the various exploring coils, the electrical circuits of the amplifiers used, and of the oscillograph and of the exciting magnet used in tests are shown diagrammatically in Figure 4. The connections from the rotating coils lead out through the shaft and are connected with slip rings, the brushes from which lead to the primary of a trans-

FIG. 1.—TURBINE DISC WHEEL TESTING MACHINE.

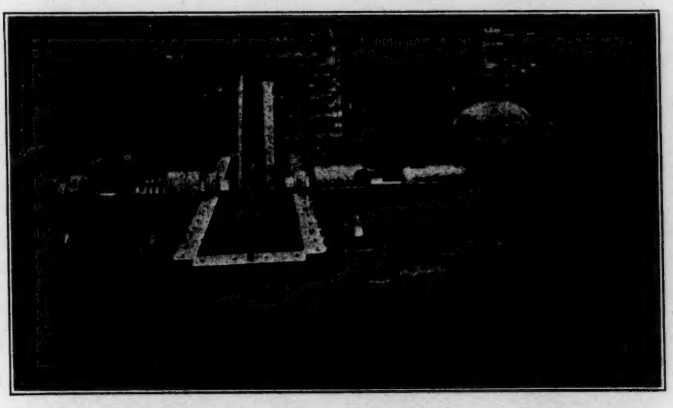

FIG. 2—MACHINE WITH TOP HALF OF CASING REMOVED.

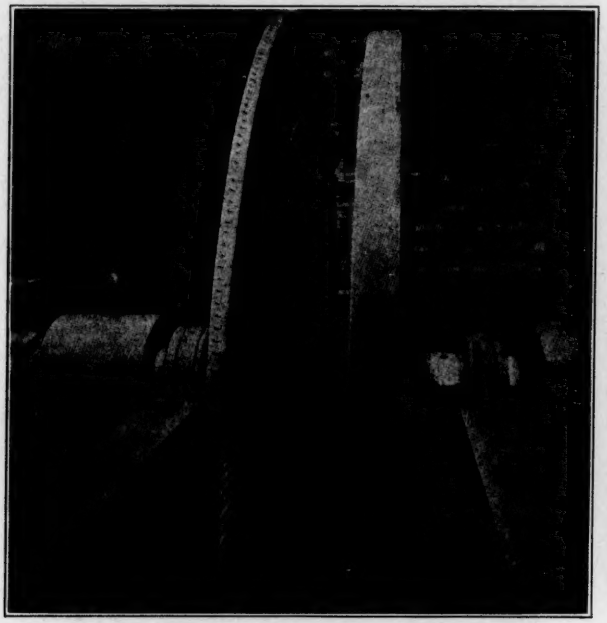

FIG. 5.—WHEELS AND COILS IN VIBRATION TESTING MACHINE.

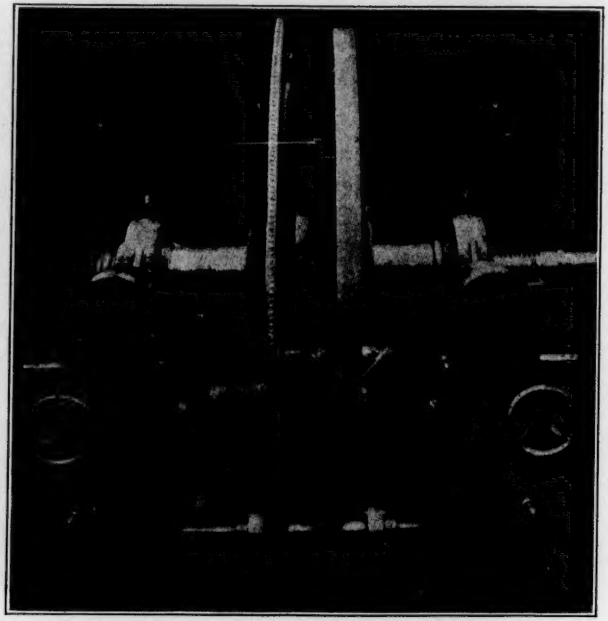

FIG. 6.—WHEELS AND COILS IN DYNAMIC BALANCING MACHINE.

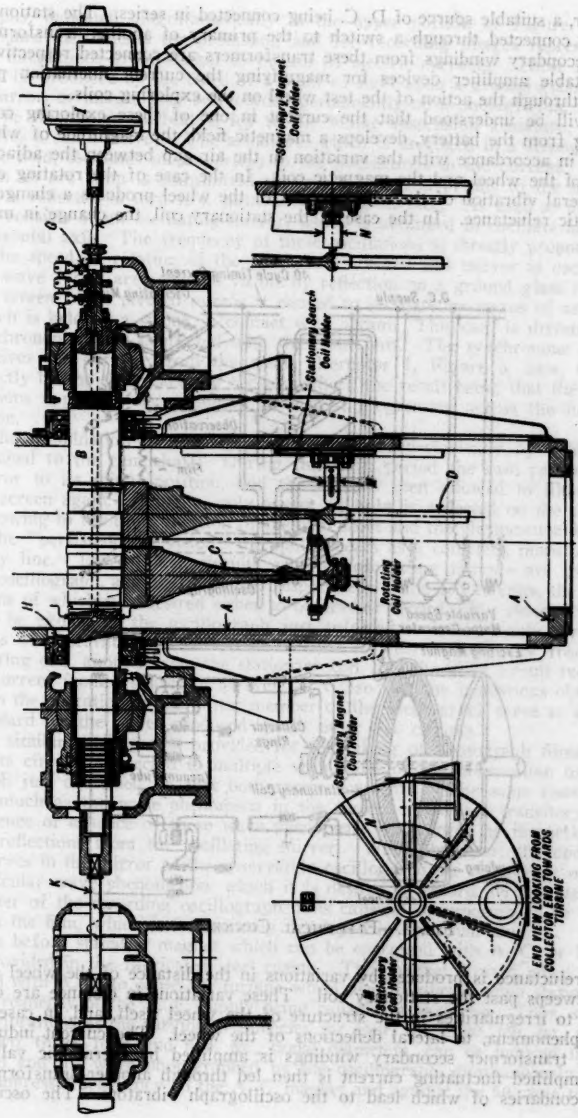
Stationary Magnet Coil Holder
Stationary Search Coil Holder
Rotating Coil Holder
Stationary Magnet Coil Holder
END VIEW LOOKING FROM COLLECTOR END TOWARDS TURBINE
Stationary Coil Holder

FIG. 3.—SECTION OF WHEEL TESTING MACHINE.

former, a suitable source of D. C. being connected in series. The stationary coil is connected through a switch to the primary of another transformer. The secondary windings from these transformers are connected respectively to suitable amplifier devices for magnifying the current fluctuation produced through the action of the test wheel on the exploring coils.

It will be understood that the current in one of these exploring coils, coming from the battery, develops a magnetic field, the magnitude of which varies in accordance with the variation in the air gap between the adjacent parts of the wheel and the magnetic coil. In the case of the rotating coil, the lateral vibration of the adjacent part of the wheel produces a change in magnetic reluctance. In the case of the stationary coil, the change in mag-

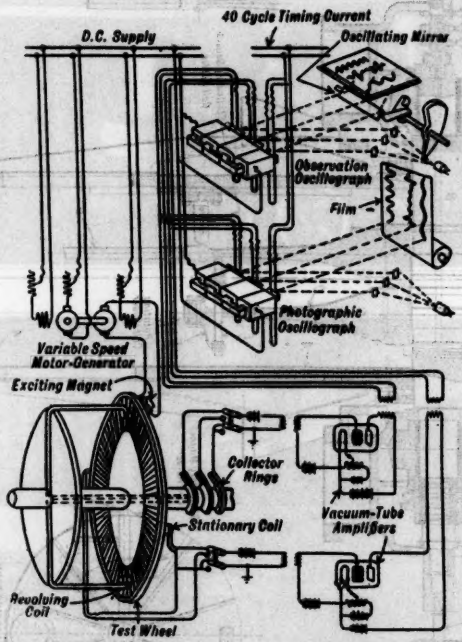

FIG. 4.—ELECTRICAL CONNECTIONS.

netic reluctance is produced by variations in the distance of the wheel rim as it sweeps past the stationary coil. These variations in distance are due, partly to irregularities in the structure of the wheel itself, and, in case of wave phenomena, to lateral deflections of the wheel. The current induced in the transformer secondary windings is amplified by thermionic valves. The amplified fluctuating current is then led through another transformer, the secondaries of which lead to the oscillograph vibrators. The oscillo-

graphs, indicated diagrammatically in the upper portion of Figure 4, are standard instruments for producing and for recording images representing the fluctuations from instant to instant of electric currents. These images may be produced by the trace of a point of light upon a ground glass or in a mirror, or images may be recorded permanently on a photographic film.

The fluctuating current is led to the bifilar suspension armature, which carries a small mirror. The armature, which is arranged in a strong magnetic field, oscillates in proportion to the fluctuations in the current. Light from an arc lamp is transmitted through a lens and prisms to the mirror, and is reflected in turn to a suitable receiving surface. As used at present, this consists of an oscillating mirror, which is arranged to oscillate about a horizontal axis. The frequency of these oscillations is directly proportional to the speed of rotation of the test wheel. When this mirror is oscillated the wave forms are rendered visible by reflection on a ground glass receiving screen. The pivoted mirror is caused to oscillate by means of an arm, which is held by a spring in contact with a cam. This cam is driven by a synchronous motor connected with the cam shaft. The synchronous motor receives the current from the small alternator I, Figure 3, *ante*, driven directly by the shaft carrying the test wheel, the result being that the wave motions appear to be stationary instead of progressing across the field of vision.

The illumination of the screen is interrupted periodically by a shutter attached to the cam shaft. During this dark period the cam returns the mirror to its initial position, and the light is then allowed to illuminate the screen again. Actually, only a spot of light is reflected on the screen, but owing to the rapid rotation of the cam shaft and the phenomenon known as the "persistence of vision," the spot appears as a complete, more or less wavy line. Three bifilar circuits carrying oscillating mirrors are used in the oscillograph, and are connected respectively to the coil circuits, the wave forms of which it is desired either to observe or record. For reasons which will be explained, the oscillograph just referred to is used only for purposes of observation. One circuit receives its current indirectly from the rotating coil, another from the stationary coil, and the third circuit receives its current from a source of 50-cycle A. C., so that the indications obtained from the operation of this latter member of the oscillograph serve as a time standard for the waves produced by the other two circuits.

A similar oscillograph, provided for the taking of photograph films, has all its circuits connected in multiple with those of the observation oscillograph just described, so that both receive currents of the same character. Inasmuch as the wave phenomena in the turbine wheel are transitory, the presence or absence of these wave phenomena is observed by inspection of the reflections from the oscillating mirror. When, however, the operator observes in the mirror of the observation oscillograph the occurrence of any particular wave phenomenon, which it is desired to record, he operates the shutter of the recording oscillograph, thus causing an exposure to be made upon the film, which is immediately developed in the usual manner.

As before stated, a magnet which can be energized with A. C. or D. C. is provided in the fabricated steel casing. This magnet is used when energized with A. C. to cause the turbine wheel disc to vibrate when stationary, the frequency of the A. C. supply being capable of variation. Thus, standing vibrations at the varying frequencies for four, six, eight, ten, &c., nodes or two, three, four, and five, &c., nodal diameters, can be induced in the wheel and the wave photographed by the oscillograph simultaneously with the impressed frequency on the A. C. magnet and against the 50-cycle timing

wave. A record of all these three observations is important for the standing frequencies at various numbers of nodes.

Figure 5 shows the shaft with the rotating coil wheel and the bladed turbine wheel disc in the bottom half of the fabricated steel case. This figure shows clearly the supports for the rotating coils spaced 180 degrees apart. Figure 6 shows the shaft with the rotating coil wheel and the bladed turbine wheel disc wheel in the dynamic balancing machine in order to ensure as perfect a balance as possible before running in the wheel testing machine.

Figure 7 gives a reproduction of the oscillograph record of a wheel tested in the wheel-testing machine when rotating at various required speeds. The stationary frequency tests are first taken for various numbers of nodes, four, six, eight, &c., or number of nodal diameters, two, three, four, &c.

As already stated, the stationary tests record on the oscillograph film the frequency of the impressed voltage on the magnet used for vibrating the stationary wheel, the frequency of oscillation of the wheel from the stationary exploring coil, and the 50 cycle per second timing wave. It has been found that, unless these frequencies are all recorded on the oscillograph film, doubt may exist as to the true natural frequency of the wheel at any given number of nodes. Cases have been recorded in which the wheel, instead of vibrating at twice the frequency of the current in the alternating magnet was vibrating at some multiple of the impressed frequency of the alternating magnet. Therefore, unless care is taken to ascertain definitely the frequency of vibration of the wheel disc when stationary, and if this test is the only test carried out—as is the practice of some manufacturers—wrong conclusions as to the safety of the discs from nodal vibration are likely to be drawn. Figure 7 shows a typical oscillograph record for a rotating turbine disc wheel in the wheel vibration testing machine. A four-node or two-nodal diameter wave train is very clearly developed in it. As the wave travels past the rotating coil the adjacent portion of the wheel oscillates backward and forwards, so as to produce the wave record marked "rotating coil." It will be seen that in the space marked one revolution as indicated, there occur two wave crests on each side of the zero line of the wave shape. Since there are two wave crests on each side of the wheel, making a total of four, this record indicates the presence of a four-node wave train or one of two-nodal diameters. The stationary coil shows a series of waves which on examination will be found to be just twice as many in number as those appearing in the rotating coil record.

The double frequency wave shown by the stationary search coil represents a wave travelling forward in the wheel. The fact that the frequency shown on the curve for the stationary search coils is exactly twice the frequency of the rotating coil, confirms the fact that we are here dealing with a critical speed phenomenon in which the backward travelling wave is stationary in space and has a forward wave superposed upon it. The interpretation therefore of the record, Figure 7, is as follows:—Four-node or two-nodal diameter critical speed; frequency, 42.7 cycles per second; revolutions per second of wheel, 21.20.

During a complete test on a turbine disc wheel, a series of records similar to Figure 7 are taken for four, six, eight, &c., nodes, or two, three, four, &c., nodal diameters. The critical speeds at which these wave trains will occur can be predicted closely from the stationary frequency records.

In addition to critical nodal speeds which, as has already been explained, are the speeds for any given number of nodes or nodal diameters in which the backward travelling wave is stationary in space, other nodal resonant speeds occur which are termed "minor resonant" speeds. In these cases the

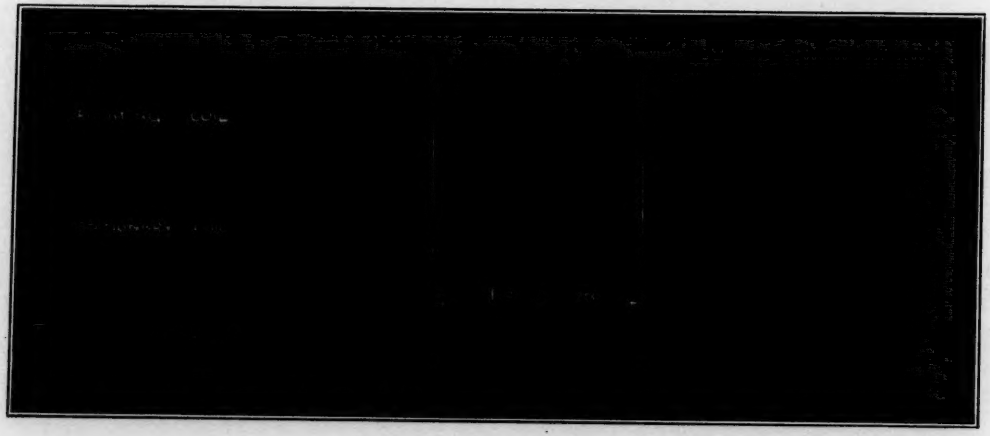

FIG. 7.—OSCILLOGRAPH RECORD.

backward running wave train is not travelling backwards as fast as the wheel disc is running forward, and therefore we can get records from the oscillograph of minor resonant speeds in which the backward running wave will record through the stationary search coil a frequency of one cycle per revolution, the rotating coil will show a frequency of three cycles per revolution, and the forward running wave train, if present, would indicate through the stationary search coil a frequency of 55 cycles per revolution. Such a record we should term a four-node first minor resonant speed. Similarly we can have a four-node second minor resonant speed where the frequencies recorded on the film per revolution would be either two or six cycles on the stationary search coil and four cycles on the rotating search coil.

Similarly minor resonant speeds occur for two, four, six, eight, &c., nodes, or one, two, three, four, &c., nodal diameters. As these minor resonant speeds cannot build up to dangerous magnitudes as compared with "critical nodal speeds," they are from the point of view of failures of the turbine wheel discs not so important. Nevertheless it is desirable, wherever possible, to safeguard the wheel discs by tuning from these minor resonant speeds in the neighborhood of the normal running speed of the unit because of the liability to produce fatigue in the wheel disc.

When a complete set of oscillograph records for stationary and running conditions has been obtained, it is analyzed and used to calculate frequency of vibration, number of nodes or nodal diameters, and revolutions per second of the wheel testing machine at which the films were taken.

The facts are shown graphically in Figure 8, which gives a diagrammatic representation that has been found to be very useful. This diagram was devised by Mr. W. Campbell, of the General Electric Company, of America. The vertical scale represents the frequency registered in an oscillograph by the magnet coils, and the horizontal scale the rotational speed of the disc. The middle curve gives the variation of frequency with speed as recorded by the revolving coil. The upper and lower curves show the two frequencies registered by the fixed coil, the upper giving the frequency due to the forward component wave, and the lower the frequency due to the backward component wave train of the nodal vibration. For instance, consider the four-node vibration. When the wheel is at rest the figure shows that both coils register 30. As the speed of the wheel is raised to 21.2 R.P.S. the revolving coil frequency rises to 42.7 and the two frequencies recorded by the fixed coil diverge. The gradual rise of frequency of the wheel as its speed is increased is expressed by the equation previously given, viz.,

$$f_r = \sqrt{f_s^2 + BN_s^2}$$

The upper curve shows how the frequency of a forward-moving wave train, as measured at a fixed point, rises relatively to the frequency detected by the revolving coil, because this wave train is carried forwards by the wheel, and is thus passing the fixed coil at a higher speed than it would were the wheel not rotating. This rise in frequency is measured by the number of wave lengths per second that the wave train is carried forward by the wheel rotation which equals the product of the number of waves on the wheel rim $1/2n$ by the number of revolutions per second of the wheel N_s. This product $1/2n\ N_s$ is the frequency in excess of that of the wheel as measured by the revolving coil; that is, in excess of f_r. If H is the higher frequency recorded by the stationary coil and represented by the upper curve, then

$$H = fr + \tfrac{1}{2} n\ N_s.$$

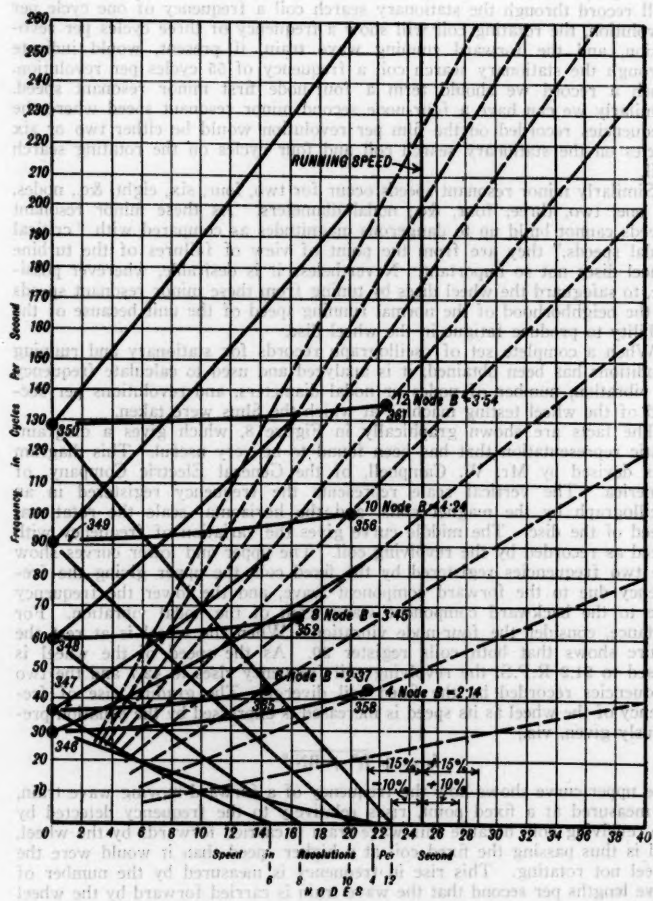

FIG. 8.—GRAPHICAL REPRESENTATION OF TEST RESULTS.

In the same way the lower curve shows how the frequency of the backward travelling wave as measured at a fixed point is decreased because in his case the wave motion is opposite in direction to the motion of the wheel. Thus if M is the lower frequency recorded by the stationary coil and represented by the lower curve,

$$M = fr - \tfrac{1}{2} n N_s.$$

If the backward moving component wave train is absent, only the upper frequency is registered by the fixed coil corresponding to a forward moving travelling wave. If the forward moving component wave train is absent, only the lower frequency is recorded, due to the backward travelling wave. The frequency recorded by the revolving coil, however, is always the same whether one or both of the component wave trains exist and in whatever relative amplitudes they exist. It is therefore evident that by the use of two exploring coils as described, one revolving with the wheel, the other being fixed in space, the presence of a forward or a backward travelling wave train or both can be detected. Furthermore, at the wheel speed of 21.2 revolutions per second the backward wave train component cuts the zero frequency line, thus showing that the nodal vibration is critical and stationary in space and the stationary coil records the high-speed forward running wave component of 85.4 cycles per second. The speed coefficient B of the turbine wheel disc under consideration gives a calculated value from the oscillograph records for four-node, *i.e.*, two-nodal diameters of 2.14

For six nodes or three nodal diameters B=2.37.
For eight nodes or four nodal diameters B=3.45.
For ten nodes or five nodal diameters B=4.24.
For twelve nodes or six nodal diameters B=3.54.

With the help of the data obtained on turbine disc wheels actually tested in the wheel vibration testing machine it is possible to proceed with certainty in developing wheels for turbines of increasingly large output, and to assure their satisfactory operation in commercial service.

An outline of the procedure followed in developing the design of new turbine disc wheels may be of interest. The first step in designing a bucket wheel is to determine the general design of the bucket, establish the dovetail required for the bucket and use the centrifugal force of the bucket to determine the general contour of the rim of the wheel. This is necessary so as to make a careful re-check when the whole design is established, to see that the tangential bucket vibration and the lateral wheel vibration are satisfactory. The determination of the thickness of hub, web and rim to avoid lateral vibration is accomplished by comparison with accumulated data on other wheels and a careful study of the actual data obtained on running wheels as to frequencies and their behavior under running conditions.

The wheel is then laid out to scale. The thickness at several points is determined to insure uniformity in shape. It is necessary to carry out this very carefully, as all our lateral wheel vibration data are based on definite curves for the shape and design of wheels used. Stress calculations made from full-size layout and curve sheets plotted. If stresses are not below the established standards, it is necessary to lay out a new design. Whether carbon steel or alloy steel is to be used for the wheel is determined by the stresses and temperatures. The positions of the steam balance holes are very carefully checked and copied in the wheel, to keep them within the established limits. At this time, the draw-off holes are also carefully considered as are the grooves for balancing weights, which happen to be either in the first or the last stage wheel of the machine.

At this point, the wheel design is turned over to the turbine drawing-office to be used in making a layout of the machine. If, after making the general

layout of the machine, the general design is found satisfactory, details are made and turned over to the calculating section for final comparison with the original layout, material called for, &c.

Should the factory, during the process of manufacture, make any departure from the drawing, it is reported to the turbine engineering department by the factory inspector, and compared with the original layout, stress and vibration data to determine whether or not the wheel can be used. A new drawing is made showing the difference between the original design and the modified one.

The turbine wheel is then tested in the vibration testing machine. The standing frequencies are taken on the temporary shaft used in the tests; also the running frequencies for all nodes as well as the vibration tendencies of the wheel, the broadness of resonance of the wheel at critical points and the general behavior of the wheel. This requires at least thirty and, in special cases, twice this number of oscillograph films on each wheel. All these films are very carefully checked and analyzed and compared with films of other wheels and those in operation, before the wheel is allowed to pass into production. It is also necessary to make diagrams from these oscillographs and compare them with others, as this is the only method of quickly determining the discrepancies in the behavior of wheels. All these films are indexed and certain data drawn from them as well as from the diagrams, which are indexed for comparative purposes.

If, after preparing these data, the wheel is found unsatisfactory, owing to running frequencies being close to the operating speed or any other causes, it is again necessary to tune the wheel and repeat the test in the vibration machine. If the wheel is found satisfactory after tuning again, we either have to change the drawings or make new ones and change all the records to agree with the wheel as finally passed into production. However, if the wheel cannot be made satisfactory by tuning, it is finally rejected. The wheel is now ready to be shrunk on the shaft, but before shrinking it on to the shaft, a careful check is made by the factory inspector of the wheel bore, the serial number and the drawing number and the diameter of the shaft. This data is turned over to the engineering department for final check to insure a tight wheel under operating conditions.

Every wheel in a new design of machine is calculated in like manner. For modified designs of machines, where any departure is made from the original design in wheels, or buckets, this same procedure applies.

This outline gives an idea of the extreme care which is taken, so as to be sure nothing is taken for granted in the matter of wheel design.—"The Engineer," April 10, 1931.

CONSTRUCTION, OPERATION AND CHARACTERISTICS OF PHOTOELECTRIC TUBES.

By Lewis R. Koller.*

The photoelectric tube which in recent years has become such a useful engineering tool is simply a valve controlling the flow of electricity. It is an incredibly rapidly acting valve, remarkably accurate, and so sensitive that it is controlled by almost infinitesimal amounts of light energy.

Although it is new to the world of applied physics, it has been known to the scientific world for some forty years and has been the subject of much

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Presented January 12, 1931

investigation. The phenomena involved are of much interest in themselves and in addition have formed one of the cornerstones upon which the theory of the corpuscular nature of light is based.

The essential fact of photoelectricity is that when light falls upon a metal surface, electrons are emitted. That is the form in which we express the fact today. Back of this simple statement lies much painstaking research. The first investigator in the field, Heinrich Hertz, discovered (quite by accident) that a spark passed more readily between two electrodes when they were illuminated by a similar spark. His successor in this field, Hallwachs, found that under the influence of light a negatively charged metal plate loses its charge. Succeeding investigators identified this loss of charge with the emission of electrons and defined the conditions under which it takes place.

Figure 1 shows the elements of a photoelectric tube. Light falls upon a metal surface (the cathode) and causes it to emit electrons. These electrons are drawn towards another electrode (the anode) which is maintained at a positive potential with respect to the cathode by means of a battery.

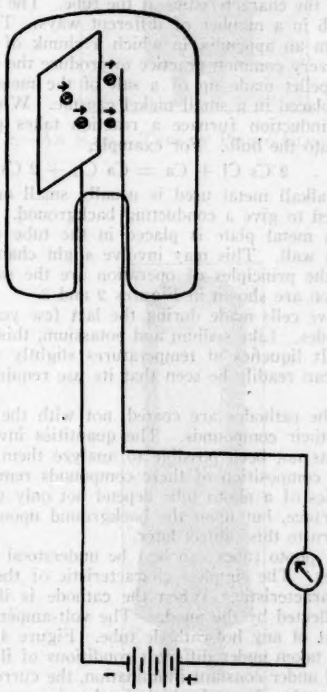


FIG. 1.—THE ESSENTIALS OF A PHOTO-ELECTRIC TUBE.

This passage of electrons from cathode to anode constitutes a current which is controlled by the light incident on the plate. The magnitude of the current as well as its reliability is greatly increased by enclosing the two electrodes in a highly evacuated glass bulb.

A complete investigation of this subject would involve a study of the effect of the cathode surface, both as regards its physical structure and its chemical constitution, the nature of the surrounding medium, the shape and spacing of the anode, the potential applied between the electrodes, the intensity, color and plane of polarization of the incident light.

The first photoelectric surfaces studied were zinc plates. A little later Elster and Geitel found that the alkali metals, sodium and potassium, were far more sensitive. That is to say, for the same quantity of light they allowed larger currents to flow. Since these metals oxidize rapidly on exposure to air and lose their metallic properties, they must be enclosed in highly evacuated glass bulbs. This fact determines the structure of most photoelectric tubes. They usually take the form of a glass bulb, one wall of which is coated with the active material. The other electrode may be of any convenient material, and of a wide variety of shapes, without very markedly affecting the characteristics of the tube. The alkali metal is introduced into the bulb in a number of different ways. The earliest way was to distill it in from an appendix in which a chunk of the metal had been placed. It is now very common practice to produce the metal directly in the bulb. A pressed pellet made up of a salt of the metal to be used and a reducing agent is placed in a small nickel capsule. When this is heated by a high-frequency induction furnace a reaction takes place and the alkali metal distills out into the bulb. For example,

$$2\ Cs\ Cl + Ca = Ca\ Cl_2 + 2\ Cs$$

The amount of alkali metal used is usually small and the bulb wall is usually first silvered to give a conducting background.

In some cases a metal plate is placed in the tube to serve as cathode instead of the bulb wall. This may involve slight changes in technique of manufacture, but the principles of operation are the same. Two different types of construction are shown in Figures 2 and 3.

The most sensitive cells made during the last few years have been made with caesium cathodes. Like sodium and potassium, this oxidizes readily on exposure to air. It liquefies at temperatures slightly above normal room temperature so it can readily be seen that its use requires a highly specialized technique.

In many cases the cathodes are coated, not with the pure alkali metals, but with some of their compounds. The quantities involved are so small, however, that it has not been possible to analyze them by ordinary chemical means and the composition of these compounds remains in some doubt.

The characteristics of a photo tube depend not only upon the metal used for the cathode surface, but upon the background upon which it is deposited. We will return to this subject later.

The operation of photo tubes can best be understood by a study of their characteristic curves. The simplest characteristic of the cell to measure is its volt-ampère characteristic. When the cathode is illuminated electrons are emitted and collected by the anode. The volt-ampère characteristic differs little from that of any hot-cathode tube. Figure 4 shows a family of volt-ampère curves taken under different conditions of illumination. As the voltage is increased under constant illumination, the current increases gradually to a saturation value, beyond which further increases in voltage cannot increase the current. The saturation current represents the condition where

FIG. 2.—AN EARLY TYPE OF PHOTO-ELECTRIC TUBE.

FIG. 3.—A LATER MODEL.

all of the electrons liberated by the light are being collected by the anode. Increasing the voltage cannot increase the current because there are no more electrons to be caught.

If the light intensity is increased, a new value of saturation current is obtained at a slightly higher voltage. In most photoelectric tubes, under ordinary conditions of illumination, saturation is obtained at voltages below 100 volts. The voltage at which a tube is to be operated should always be above the knee of the curve in order that the anode may capture all the electrons liberated by the light and give a response proportional to the illumination.

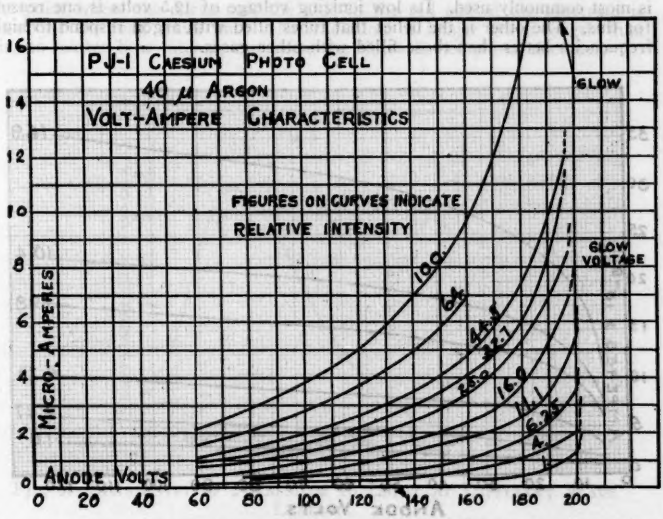


FIG. 4.—VOLT-AMPERE CHARACTERISTICS OF PJ_5 (VACUUM) CELL UNDER DIFFERENT ILLUMINATIONS.

If a little gas is present in the tube, the characteristics are radically different. The current no longer saturates but continues to increase with increasing voltage, at first gradually and later more or less abruptly, depending upon the illumination. This is due to collisions between electrons and gas molecules in the space between the electrodes, which results in ionization of the gas. The result of each such collision is the liberation of another electron and the formation of a positively charged gas ion. This is in effect an increase in current.

Increasing the anode voltage increases the number of the ionizing collisions, so that the current continues to rise as the voltage is increased. The process is a cumulative one and finally reaches a stage where each electron takes part in several ionizing collisions while passing from cathode to anode. The discharge then passes over into an ordinary glow discharge. At low light intensities this transition is very abrupt. At high light intensities, it is so gradual that it is not apparent by inspection of the volt-ampère curve.

The glow may be so feeble that it is not visible. The condition is easily recognized, however, as if the light source is shut off the current still continues to flow. Gas-filled tubes should always be operated at voltages low enough so that they will not glow under the highest illumination to which the tube is to be subjected.

The advantage of introducing gas is, of course, that due to the ionization, the current is greatly increased, in some cases as much as ten fold. The choice of gases is rather limited as the gas must be one which does not react with the cathode material and one which does not clean up in the electric discharge. This limits the choice to the rare gases of the atmosphere. Argon is most commonly used. Its low ionizing voltage of 12.5 volts is one reason for this. The other is the belief that tubes filled with argon respond to high frequencies better than those filled with other gases.

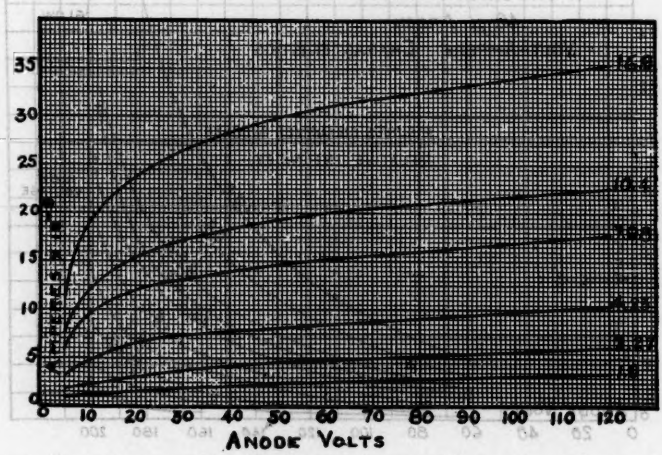


FIG. 5.—VOLT-AMPERE CHARACTERISTICS OF PJ1 CAESIUM CELL CONTAINING ARGON.

The time required for photoelectric response is extremely small. Measurements have been made which show that the effect is practically instantaneous. The current begins to flow within less than 10^{-9} seconds of the time that the light falls on the cathode. Accordingly, vacuum-type tubes give a current which reproduces faithfully any variations in light intensity with no lag other than that due to the inductance and capacity of the electrical circuit. In the case of gas-filled tubes, there is a slight time lag which results in a falling off in tube response as the frequency is increased. While this is very slight at a few hundred cycles, it becomes quite appreciable at several thousand cycles.

One of the most useful characteristics of photoelectric tubes is the relation between current and illumination. This is strictly linear over a very wide range. It is this characteristic that makes the photoelectric tube so useful as a measuring device. The photo current per unit of light flux or sometimes of light intensity is called the tube sensitivity.

In speaking of sensitivity of different cathode materials we have overlooked the fact that the response to light is not uniform throughout the spectrum. Most photosensitive materials show a greater response to blue light than to an equal amount of radiant energy in the red end of the spectrum. The wave-length sensitivity curve for potassium is shown in Figure 6. The ordinates of this curve represent the relative photo currents obtained when the tube is exposed to equal amounts of energy of light of different wave lengths. It shows a sharp maximum near the blue end of the spectrum. This maximum would be much broader were it not for the absorption of the glass which prevents the ultra-violet radiation from reaching the cathode. The point where the curve cuts the axis in the red end of the spectrum is known as the long wave limit. No radiation of longer wave length than this, no matter how intense, can cause the liberation of photo electrons.

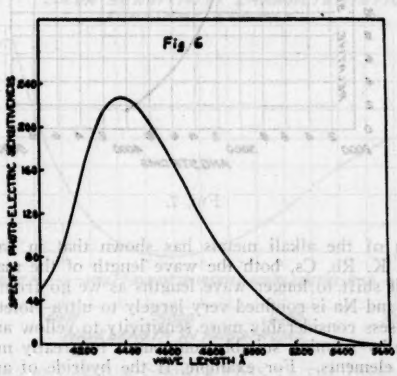


FIG. 6.—SENSITIVITY OF POTASSIUM TO LIGHT AT DIFFERENT WAVE LENGTHS.

From this curve it can be seen that the photoelectric tube, like the human eye, is a selective device. It does not give the same response for equal amounts of energy of light of different wave lengths, as a thermopile or radiometer does. Its sensitivity is best for blue light and least for red. This is typical of most of the metals. Each one has a curve, of which the wave length of the maximum response and the long wave limit are quite characteristic. To a certain limited extent it is possible to construct a tube sensitive to any desired part of the spectrum. The chief limitation is the fact that the sensitivity of each of the metals except those of the alkali metal group is so low that they are useless for practical purposes.

For measurements of ultra-violet radiation, sodium cathodes in quartz bulbs are used. These have comparatively little response to visible light as can be seen from this spectral sensitivity curve Figure 7. By means of suitable filters it is possible to measure the radiation in rather broad regions very satisfactorily. Due to the fact that filters do not have sharp cut-offs, it is not possible to study very narrow bands by this method and a monochromator must be used.

Most applications of photoelectric tubes make use of incandescent light sources. Figure 8 shows the characteristics of the radiation from such a source. From this figure it can be seen that this lamp radiates most of its energy in the longer waves and comparatively little in the blue region to which the photoelectric cell is most sensitive. Anything which extends the response curve of the photo tube into the red will result in a great increase in its sensitivity to incandescent light sources.

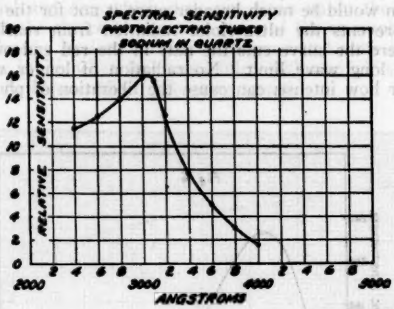


FIG. 7.

Investigation of the alkali metals has shown that in passing down the series, Li, Na, K, Rb, Cs, both the wave length of the maximum and the long wave limit shift to longer wave lengths as we go from Li to Cs. The response of Li and Na is confined very largely to ultra-violet radiation while Rb and Cs possess considerably more sensitivity to yellow and red light.

It is possible by forming suitable compounds to greatly modify the sensitivity of these elements. For example, if the hydride of any of these elements is formed, the entire wave length sensitivity curve is shifted to the

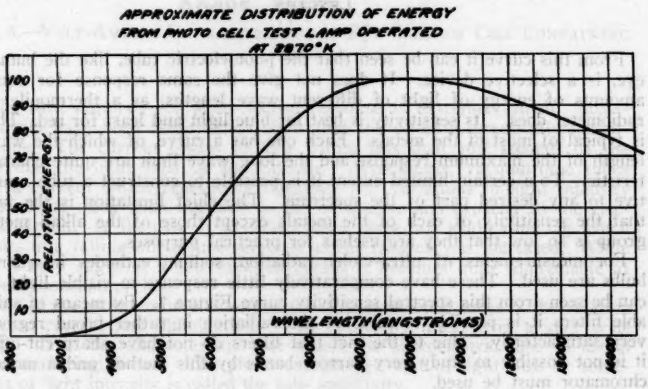


FIG. 8.

right of the curve for the pure metal. Other compounds show still more striking effects. For example, the oxides of caesium result in a very pronounced peak in the near infra red as shown in Figure 9. This peak may be as high or higher than the blue peak. It adds tremendously to the usefulness of the tube as it occurs in a part of the spectrum where most incandescent sources radiate a great deal of energy.

Analagous effects have been obtained with a great many other compounds of the alkali metals. The phenomena are as yet in the empirical stage and are not very well understood.

The photoelectric behavior of the alkali metals also depends upon the thickness of the layer and on the background upon which they are deposited as well as on the nature of the alkali metal itself.

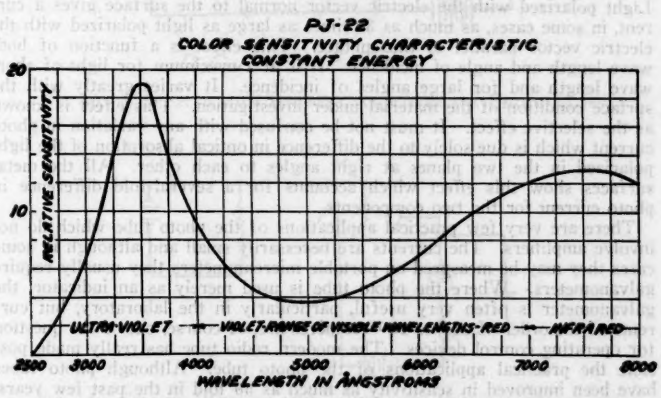


FIG. 9.—OXIDES OF CAESIUM SHOW A PEAK IN THE INFRA-RED REGION.

If a tube is connected in series with a sensitive meter, a small current will be observed to flow when the tube is illuminated, even though there is no source of voltage in the circuit. This is due to the fact that the electrons which are emitted by the light are actually ejected with definite, though small, initial velocities which enable them to pass across the interelectrode space and overcome the resistance of the external circuit. The initial velocity of the electrons is determined by the wave length of the incident light and not by its intensity. The shorter the wave length the higher will be the initial velocity with which the electrons are ejected. These initial velocities are always low, of the order of a volt, and for all practical purposes are negligible in comparison with the velocities acquired due to the anode voltage. Their study has been of fundamental importance, however, in the development of the quantum theory. In 1905 Einstein first proposed the relation

$$Ve = hv - hv_0$$

This states that the energy of the escaping electron (its charge, e, times its velocity in volts, V) is equal to the energy of the quantum which caused its ejection minus the energy which it was necessary for the electron to lose on passing through the metal surface. In other words, each quantum causes

the emission of one electron. This electron escapes with the entire energy of the quantum minus whatever energy the electron needed to overcome surface forces.

This theoretical relation was later verified by Millikan and has been the subject of investigation by many others since then. The effect of increasing the intensity of the incident light will be to cause the emission of more electrons, but the maximum velocity of each electron is limited by the energy of the light quantum which caused its ejection.

Another effect which at present is more of academic than practical interest is the behavior of tubes towards polarized light. Most materials do not show any variation in photoelectric effect with rotation of the plane of polarization. The alkali metals, however, show a very marked effect. Light polarized with the electric vector normal to the surface gives a current, in some cases, as much as 30 times as large as light polarized with the electric vector parallel to the surface. This effect is a function of both wave length and angle of incidence. It is at a maximum for light of short wave length and for large angles of incidence. It varies greatly with the surface condition of the material under investigation. This effect is known as the selective effect. It must not be confused with any variation in photo current which is due solely to the difference in optical absorption of the light polarized in the two planes at right angles to each other. All the metal surfaces show this effect which accounts for a several-fold difference in photo current for the two components.

There are very few practical applications of the photo tube which do not involve amplifiers. The currents are necessarily small and although in some cases they may be measured on portable microammeters they usually require galvanometers. Where the photo tube is used merely as an indicator, the galvanometer is often very useful, particularly in the laboratory, but currents of the order of 10^{-6} to 10^{-12} ampères are, of course, out of the question for operating control devices. The modern radio tube has really made possible the practical applications of the photo tube. Although photo tubes have been improved in sensitivity as much as 50 fold in the past few years, they would be quite useless without the many-fold amplification which the three-electrode tube has placed at our disposal.

The simplest and probably the commonest type of amplifier for photo tubes is the resistance coupled direct current amplifier shown in Figure 10. A high resistance of from 1 to 10 megohms or even more is placed in the tube circuit and the drop across this resistance applied between the grid and filament of the amplifier tube. This resistance is small compared with the internal resistance of the photo tube so that it does not appreciably affect the photo current. Increasing photo current results in increasing iR drop which results in an increase or decrease in plate current depending upon which end of the resistance has been connected to the grid of the pliotron.

With this arrangement when the photo tube is in the dark the pliotron passes a plate current which depends upon the grid bias used and the response is not a linear one. The circuit can be modified so as to give zero amplifier current for zero photo current and to give a response proportional to the photo current by the arrangement shown in Figure 11. By suitable adjustment of the resistance R the plate current for no light on the photo tube is balanced out and the meter only indicates the difference in plate current due to the photo current. If the pliotron has been properly biased so as to work on the straight portion of the characteristic, these deflections will be proportional to photo currents. This is a very useful circuit. Its chief drawback is that it does not stay in adjustment but must be frequently balanced.

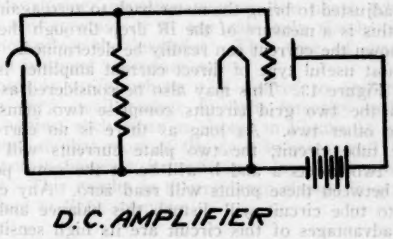


FIG. 10.—CIRCUIT OF THE SIMPLEST AMPLIFIER FOR PHOTO TUBES.

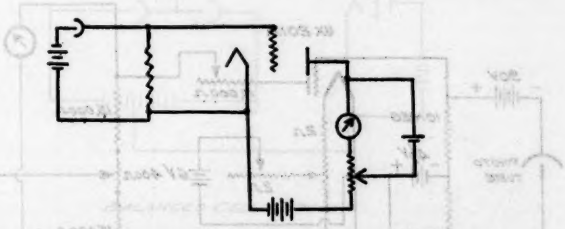


FIG. 11.—CIRCUIT WHICH GIVES A RESPONSE PROPORTIONAL TO THE PHOTO CURRENT.

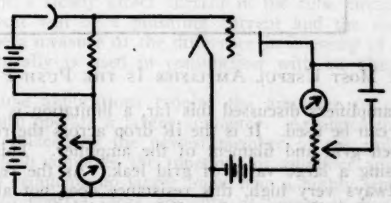


FIG. 12.—A USEFUL CIRCUIT FOR SINGLE OBSERVATIONS.

A slight modification of this circuit which is useful where it is only necessary to make a single observation is shown in Figure 12. This circuit is identical with the one shown in 11 except that a potentiometer is included in the grid circuit. After reading the deflection due to photo current the potentiometer is adjusted to bring the meter back to zero again. The voltage necessary to do this is a measure of the iR drop through the grid leak and since the R is known the current can readily be determined.

Perhaps the most useful type of direct current amplifier is the push-pull circuit shown in Figure 13. This may also be considered as a Wheatstone bridge of which the two grid circuits comprise two arms and the two plate circuits the other two. As long as there is no current flowing in the photoelectric tube circuit, the two plate currents will be equal and consequently the two points a and b will be at the same potential, and a meter connected between these points will read zero. Any current flowing through the photo tube circuit will disturb this balance and give a meter deflection. The advantages of this circuit are its high sensitivity, the proportionality between input and output over a wide range, and the fact that it is not affected by changes in battery voltage.

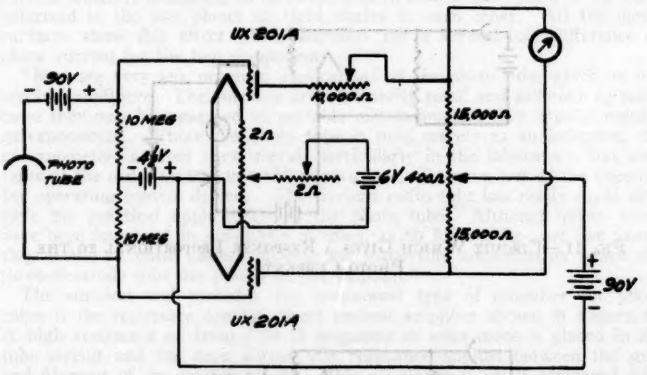


FIG. 13.—THE MOST USEFUL AMPLIFIER IS THE PUSH-PULL CIRCUIT.

In all of the amplifiers discussed this far, a limitation is the size of the grid leak which can be used. It is the iR drop across the resistance which is applied between grid and filament of the amplifier. This can be made quite high by using a large value of grid leak. As the resistance of the photo tube is always very high, this resistance does not affect the photo circuit appreciably, but if it is made sufficiently high it may be comparable with the amplifier tube leakage. This is a rather uncertain quantity depending upon the history of the tube, atmospheric conditions, etc., and the results are apt to be quite unreliable. A tube has been developed recently which is particularly suitable for amplifying photo currents. One of its chief advantages is the fact that the input resistance of the grid circuit is of the order of 10^{16} so that it may be used in conjunction with extremely high resistances in the photo tube circuit. It is with this tube that currents of the order of 10^{-18} ampères have been measured.

In the case of very small currents, the photo electric current may be comparable with the leakage or dark currents. In such cases it is advantageous to use alternating current amplification. This is done by modulating the light source (either mechanically or electrically) and using either condenser or transformer coupling between the photo tube and amplifier circuits. Thus any constant or at any rate only slowly changing leakage currents will not affect the amplifier. This type of amplification is, of course, also used in sound reproduction.

A circuit which is useful where it is desired to perform some control operation on a very small change in light intensity makes use of two tubes balanced against each other as shown in Figure 14. In the dark the circuit is adjusted so that most of the drop is across cell No. 1. As soon as light falls upon it, however, its resistance drops and most of the voltage is across No. 2. This results in a very large change in grid voltage for a very small change in light intensity.

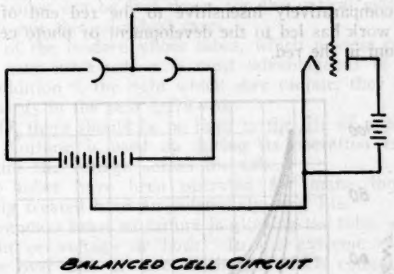


FIG. 14.—THE BALANCED CIRCUIT IS VERY SENSITIVE.

Another method of using photo tubes allows light from two sources alternately to fall upon the tube. If both sources are equal in intensity the result will be a steady direct current in the tube circuit. If they are unequal, the result will be a pulsating current and the magnitude of the pulsations will be a measure of the difference in intensity of the two beams. This circuit naturally is used in conjunction with an alternating current amplifier.

Most photo tube applications require the amplifier to operate a relay which may in turn operate a larger contactor. Arrangements of this kind are now being replaced by the newest member of the radio tube family, the thyratron which combines the functions of amplifier and relay. It has the advantage of requiring no larger input than a highly sensitive relay and yet being able to control large amounts of power in the output circuit. Furthermore, since it has no mechanical parts and no inertia it can operate at very high frequencies.

The photo electric tube is often referred to as an electric eye. The analogy is a fair one provided it is not carried too far. Strictly speaking its only resemblance to the eye is the fact that it responds to light. The nature of the response is a very different one. A comparison of the relative sensitivities of the tube and the eye is very interesting. The dimmest star which can still be seen with the naked eye is designated by the astronomers as a

sixth magnitude star. The amount of light which would reach the unaided eye from such a star would be 5.5×10^{-13} lumens. If we allow this same flux to fall upon the best photo electric tube which we can produce at present the resulting current will be 1.1×10^{-16}. With the best amplifier available at present we can detect a current of 0.5×10^{-18} ampères or in other terms 30 electrons per second. This is approximately 1/20th of the current which we would obtain from the sixth magnitude star so that the photo tube with a good amplifier is 20 times as sensitive as the eye. The unaided eye, however, is a far more sensitive detector of radiant energy than the photo electric tube without an amplifier.

The photo tube, like the eye, is a selective device in that its response is not the same throughout the spectrum, but it sees some one wave length better than any other and gives a smaller response to both longer and shorter wave lengths. In the case of the eye this maximum response comes at a wave length of 5500Å that is in the yellow green part of the spectrum. The eye is relatively less sensitive to blues or reds. In the case of the photo tubes, most of the pure metals show a maximum in the blue or the ultra-violet and are comparatively insensitive to the red end of the spectrum, although recent work has led to the development of photo cells which show a second maximum in the red.

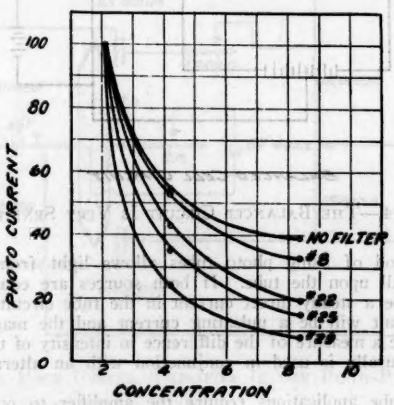


FIG. 15.

In a number of applications, the photo tube is used to record or to control some process, the progress of which is indicated by a change in the density of a transparent medium. If this medium is colored as is often the case, it is advantageous to use a color filter in the optical system. This is due to the fact that the relation between the concentration of the solution and its light transmission depends upon wave length. If we remove (by filtering) those wave lengths which are least affected by changing the concentration of the solution, we will have a proportionately greater change in light intensity for the remaining wave lengths. This, of course, will result in a greater percentage change in photo current. In general, the filter should

transmit the color of light which is most strongly absorbed by the solution. This will, of course, greatly reduce the total photo current. This may be partly compensated for by increasing the intensity of the light source.

Figure 15 shows the relation between total photo current and concentration of a $CuCl_2$ solution, using a number of different filters. The curves show that, whereas with no filter a change in concentration from 2.1 to 8.4 per cent only decreases the photo current 61 per cent, by using a suitable filter the same change in concentration will produce a 92 per cent change in current.

It is of great importance in many photo tube applications to have a constant light source. If a very constant line voltage is not available, an automobile headlight lamp can be used, operated from a storage battery.

The intensity of the beam can usually be increased by the use of suitable lenses and reflectors.

The effects of stray light can be avoided by placing a long tube in front of the cell so that the only light which reaches the cell is that which comes directly from the source.

No general rules can be laid down for the optical systems, which must be designed to suit the individual cases.

With most of the modern photo tubes, which possess considerable sensitivity in the near infra-red, it is most advantageous to use incandescent sources. In addition to the light which they radiate, they also radiate large amounts of energy in the near infra-red.

Theoretically, there should be no limit to the life of a properly exhausted photo tube. Nothing is used up during its operation except the battery which maintains the voltage across the tube.

In practice tubes have been operated for many thousands of hours and if properly treated have an indefinitely long life.

The most common cause of failure is glowing the tube, which is caused by excessive light or voltage or both. In the extreme case the glow discharge passes over into an arc discharge which completely destroys the tube. In less extreme cases there is a positive ion bombardment of the surface which actually knocks atoms off of the surface and so alters the sensitivity. This takes place in a glow discharge in a gas-filled tube and even to some extent in a vacuum tube. In even the highest vacuum which we can produce there are many millions of atoms per cubic centimeter. Some of these will be ionized by collision with electrons and will bombard the cathode surface causing more or less disintegration. Their effectiveness in this bombardment depends upon their velocity which is determined by the voltage applied between the cell terminals. This should be kept as low as possible with due regard for the characteristics of the circuit involved.

Large photo currents, in themselves, are not as a rule injurious to photo tubes, but the light intensities necessary to produce such currents may cause heating of the cathode. Where very intense light sources are to be used, it is necessary to remove the heat energy by filtering through water.

Photo tubes should never be used where the ambient temperature is greater than 50 degrees C.

Variations in tube construction are of relatively little importance to the user. Large tubes can collect more light than small ones, but the same effect can be obtained from a small tube by concentrating the light with a lens or mirror. A photo tube responds to light *flux* and not light *intensity*.

The arrangement of the lead-in wires may affect the insulation, although in most applications the photo currents are large compared with the leakage so that the factor is negligible.

Where great constancy in operation is required, vacuum tubes should be used. They have the additional advantage of not being affected by fluctuations in anode voltage. Gas filled tubes, of course, are far more sensitive, but *usually* this is gained at the expense of stability.

Photoelectric tube applications are becoming more numerous every day. The best known are probably television and talking pictures. Others are smoke detectors, counters, bean sorters, light recorders, color analyzers, physical photometers and innumerable control devices. As engineers gain a knowledge of the properties and limitations of photoelectric tubes, they will doubtless find many more uses for them.—"The Western Society of Engineers," February, 1931.

CASE-HARDENING WITH AMMONIA GAS.

By V. O. Homerberg and J. P. Walsted, Department of Mining and Metallurgy, M. I. T.

It has been the dream of metallurgists for many years to produce a steel of good toughness with maximum surface hardness and wear resistance. To produce these properties with a minimum of distortion has been the subject of much research work of a high order. In the past the most successful method of obtaining these properties has been by subjecting low-carbon steel to the action of a carburizing material at high temperatures. Under these conditions the steel takes up carbon in its surface layer, changing that portion of the material into a high-carbon steel capable of hardening, while the core remains low in carbon with the usual toughness and shock-resisting properties. By a suitable double heat-treatment the core can be brought to maximum physical properties while the case can be made hard and wear-resistant. This process of case-hardening by means of carbon is somewhat cumbersome. The necessary heat-treatment after carburizing is a frequent cause of distortion of the hardened parts.

A new process of case-hardening has been developed which has all the advantages of the older method. Besides being free from the troublesome warpage it surpasses the older method in the hardness of the case produced. The classic research of Doctor Fry at the Krupp Works, Essen, Germany, is responsible for the introduction of this valuable metallurgical development. Research of a very high order in France and in this country has brought the process to its present high state of development.

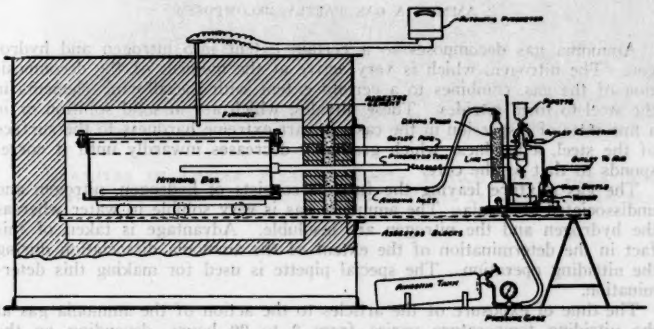
The investigation conducted by Dr. Fry began with a consideration of the combining power of various alloying elements toward nitrogen and the stability of the resulting nitrides. He found that aluminum ranked first, both as to the amount of nitrogen with which it combined as well as the stability of the aluminum nitride formed. This compound showed no loss in nitrogen even when heated at 1832 degrees F. Other elements which formed nitrides with high nitrogen contents include chromium, vanadium, titanium, tungsten, molybdenum and manganese.

STEELS EXPOSED TO AMMONIA ACTION.

Plain carbon steels, various alloy steels, including those containing aluminum and aluminum together with various other elements such as chromium and molybdenum, were subjected to the action of ammonia gas under definite conditions and the resulting surface hardness was determined in each instance. The outcome of this investigation was the manufacture of a series

of alloy steels containing varying amounts of carbon, together with approximately 1-1.25 per cent aluminum, 1-1.5 per cent chromium and 0.2 per cent molybdenum. Alloy steels having this particular combination of alloying elements were chosen because they showed the maximum surface hardness when exposed to ammonia gas under definite conditions. Furthermore, this hardness was retained at elevated temperatures and the specimens showed a marked resistance to atmospheric, water and salt water corrosion.

The process of case-hardening these steels with ammonia gas at the low temperatures designated by Dr. Fry is termed "nitriding." The temperatures used generally range from 900 degrees F. to 1000 degrees F., 975 degrees F. being the most common.



DRAWING OF INTERIOR OF NITRIDING FURNACE. THE PARTS ARE RUN IN ON A CONVEYOR AND EXPOSED TO THE ACTION OF AMMONIA GAS FOR A PERIOD OF TIME DEPENDING ON THE HARDNESS DESIRED.

The Fry process for case-hardening with ammonia offers many decided advantages in that all of the heat treating of the articles is done before the nitriding and no further treatment is necessary after their exposure to the ammonia gas. The temperature used is so low that no appreciable warping or distortion will take place provided that all of the strains produced in machining and in hardening have been removed.

The articles to be case-hardened should be machined and then heat-treated to give the desired physical properties for the core. All traces of decarburization and all strains must be eliminated before the subjection of the articles to the ammonia treatment.

The equipment required for the case-hardening of articles with ammonia consists of a suitable furnace provided with automatic temperature control, an air-tight container, which should be made of a material not susceptible to nitride hardening, a tank of ammonia provided with a suitable needle valve for controlling the flow of the gas and finally, a special pipette for determining the extent of the ammonia dissociation.

The diagram gives a schematic outline of the required apparatus. The tank of ammonia must be placed in a position such that the bent tube inside of the tank has its open end in the gaseous atmosphere and does not dip into the liquid ammonia. A suitable needle valve together with a pressure gauge insures the control of a steady and even flow of the gas. Although anhydrous ammonia is a commercial product, the final traces of water can

be removed, if so desired, by passing the gas through a tower containing lime. The inlet and the outlet tubes are made of nickel and the articles in the box are supported on nickel gauze. The inlet tube extends along the bottom of the box to the back while the outlet tube is at the front and near the top of the box. Pyrometers are inserted into both the container and the furnace. The gas mixture from the container passes through a wash bottle to indicate the back pressure, which should be about one-half inch, as well as the rate of flow of the gas, and finally passes into the atmosphere or is washed into the drain in the sink by means of a suitable baffle.

An important development in a nitriding furnace makes use of a fan to effect gas circulation.

AMMONIA GAS PARTLY DECOMPOSED.

Ammonia gas decomposes to a certain extent into nitrogen and hydrogen. The nitrogen, which is very active at the moment of the decomposition of the gas, combines to a certain extent with the alloying elements in the steel to form nitrides. These nitrides, which are in solid solution or in a fine state of dispersion in the case, impart extreme hardness to the surface of the steel, a hardness which gradually decreases inwardly until it corresponds to that of the core.

The gas mixture leaving the furnace consists of hydrogen, nitrogen and undissociated ammonia. The ammonia gas is very soluble in water whereas the hydrogen and the nitrogen are insoluble. Advantage is taken of this fact in the determination of the extent of the ammonia dissociation during the nitriding operation. The special pipette is used for making this determination.

The time of exposure of the articles to the action of the ammonia gas at the nitriding temperature varies from 2 to 90 hours, depending on the service to which the articles are to be subjected. No heat treatment is given to the parts after nitriding, the articles being cooled in the box, generally to room temperature.

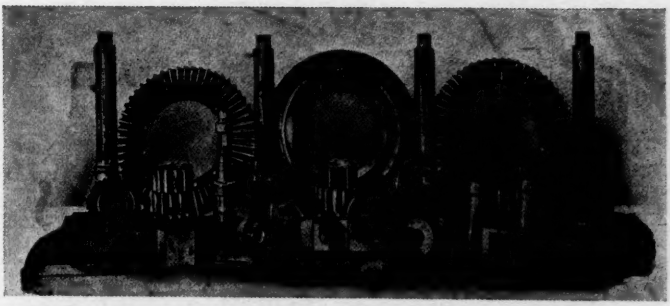
A slight growth takes place during nitriding. This growth can be allowed for in the final machining or grinding before nitriding, or it can be removed afterwards by lapping or by other suitable means.

A greater surface hardness can be obtained by this method of case-hardening than by any other means. The common method of case-hardening produces a surface hardness of 650 Brinell, whereas a hardness of 1000 Brinell is common with the Fry process.

Another valuable property which accompanies the extreme surface hardness of nitrided nitralloy is the resistance to atmospheric, water and salt water corrosion. The maximum resistance to corrosion is exhibited by the unpolished surface. In view of this fact, it is preferable to place nitrided articles directly into service without additional polishing whenever the question of corrosion is involved. It is obvious that this property of rustlessness together with extreme surface hardness renders nitrided articles highly desirable for a great many purposes.

Nitrided steel retains great hardness at elevated temperatures. It shows practically the same degree of hardness when tested at 1000 degrees F. as at room temperature and shows an excellent degree of hardness when tested at 1400 degrees F.

The use of nitrided steel in various commercial operations has fully demonstrated its great wearing properties. Many instances of actual service tests might be mentioned.



EXAMPLES OF LARGER WEARING PARTS WHICH HAVE BEEN MADE OF NITRIDED STEEL. THE LIFE OF SUCH PARTS IS MARKEDLY INCREASED BY THE USE OF SUCH STEEL.

PHOTO-MICROGRAPH OF A CROSS-SECTION OF NITRIDED STEEL SHOWING PENETRATION OF THE HARDENING ACTION OF AMMONIA GAS. ENLARGED FIFTY DIAMETERS.

Guillet has studied the wearing properties of nitrided steel especially with respect to the automotive industry. Some of the data presented by him are included in the following table:

WEAR OF CYLINDERS.

1. On car with cast-iron cylinders after 30,000 Km. (18,630 miles, inch	0.016
On car with nitrided cylinders, inch	0.0008
2. Aviation motor after 100 hours running.	
Wear of cylinders of heat treated steel, inch	0.0032-0.004
Nitrided cylinders, inch	0

Oil consumption (same conditions) per H. P. hour.

	New Motor	After 100 hrs.
Cylinder of heat treated steel	4-5 grams	12-15 grams
Cylinder of nitrided steel	4-5 grams	4-5 grams

Coste and Bellonte in their trans-Atlantic flight used a motor in which the cylinders, regulating mushrooms, tappet faces and timing gears were made of nitrided steel.

Some of the uses of nitrided steel follow: Crankshafts, Wrist Pins, Spinning Rings, Spindles, Pinions, Steam Nozzles, Cams, Bushings, Valves, Timing Gears, Small Gears, Clutches, Ring Gears, Celluloid Molds, Brick Molds, Die-Casting Molds, Worms, Chucks, Camshafts, Piston Pins, Relay Shafts, Paper Rolls, Master Cams, Gauges, Pump Shafts, Rollers, Piston Rods, Drawing Dies, Master Gears, Tappets, Steering Mechanism, Sectors, Steering Sectors.

A great deal of attention is being given to the nitriding of special tool steels and cast iron. Present results indicate that these materials in the nitrided condition will play an important part in special applications where resistance to wear is of paramount importance.

In view of the properties of nitrided steel, it can be truthfully stated that its level development represents one of the most important metallurgical accomplishments in recent years.—"The Tech Engineering News," April, 1931.

CORROSION AND HEAT RESISTING STEELS.

By F. J. McNiff, Sales Engineering Department, Industrial Steels, Inc.

The aim of this article is not to present a technical discussion of the many phases of the above subject, but rather to collect and clarify the outstanding facts which have a bearing on the manufacture and ultimate use of such alloys. To properly appreciate the value of these steels, it might be well to recall to mind the fact that 25 per cent of the world's tonnage of iron and steel is lost by rust every year. Stainless steel is playing an active part in the fight to reduce the appalling losses due to rust and corrosion.

The first phase of the problem to consider is the importance of chromium. The effect which this alloy has on retarding corrosion has been known for years, and recently much study was made of the effect of the associated carbon content. The result has been the production of the present types of stainless steel and iron. Chromium is the most valuable element now used in the production of alloy steel, due to its diversified properties. It

is obtainable in large quantities from many sections of the globe, in such quantities in fact, that in the event of another upheaval such as the World War, it would not be necessary for any country to curtail its use.

Due to a clear understanding of its properties, it is now possible to produce a number of corrosion resisting alloys with which almost any required degree of hardness and strength can be obtained, as well as various combinations of toughness and elasticity. They are sufficiently resistant to such a wide range of corroding media as to be of inestimable value for engineering purposes.

It might be well, before going further, to clear up a very widespread misunderstanding of the terms "stainless steel" and "stainless iron." The terms steel and iron are generally considered to mean those ferrous materials that are capable or are not capable of being affected by heat treatment. Since stainless metals with as low as .07 per cent carbon can be heat treated with considerable change in physical properties it will be plainly seen that "Stainless steel" and "Stainless iron" are misnomers. It would seem wiser, therefore, when investigating the possibilities of the stainless metals, to specify chemical compositions rather than the general terms commonly used.

In choosing the proper type of stainless for a particular application the problem should be approached with a full knowledge of all of the factors entering into this application. The exact nature of the corroding agent, the temperature if above normal, whether the action is continuous or intermittent, the manner in which the metal is to be fabricated, and whether or not the material is to be welded, brazed, soldered, etc., are all questions of vital interest if the maximum efficiency is to be obtained.

The characteristics of the various types, which will be shown in following paragraphs, will demonstrate how necessary it is to use the right metal for each particular use.

Another factor of prime importance in selecting the proper metal is the fact that the stainless metals are the most difficult to produce satisfactorily, and, more than any other steel, reflect the care and workmanship and general steel making ability of the manufacturer. Experience has shown stainless to be the most susceptible to internal segregation, non-metallic inclusions, and surface seams of any alloy steel.

TYPES.

The stainless metals may be roughly divided into six different types, as follows: Stainless Steel, Stainless Iron, Free Cutting Stainless Iron, 18 and 8 Chrome-Nickel, Chrome Iron and Special Heat-resisting.

The distinction between Stainless Iron and Free Cutting Stainless Iron is made because of some problems in connection with hardness and physical properties, which will be discussed in more detail in later paragraphs.

The type generally known as Stainless Steel was first adopted for use in cutlery, and this is perhaps its largest application, although it has been used to some extent in valves for automobile engines. It is an air-hardening alloy used where resistance to corrosion plus a high degree of hardness and resistance to abrasion is required. It is somewhat lacking in toughness and ductility but is very hard at temperatures up to 950 degrees-1000 degrees F.

The approximate chemical composition of stainless steel is as follows: chromium 13.00 — 20.00 per cent, carbon .30 — .65 or .65 — 1.5 per cent.

Being air-hardening, the steel must be annealed after forging if machine work is required. In all heating operations, it is necessary to preheat and hold longer at temperature than ordinary steel. Frequent reheating is

advised when forging. Oil quenching is recommended for all of the stainless steels, although very light sections may be quenched in an air blast, with slight sacrifice of hardness. Great care must be taken with the grinding of this material; it must be deep and thorough, and all traces of scale must be removed.

With the higher carbon types of stainless steel, slightly higher annealing and hardening heats must be used. Annealing should be done at 1625 to 1675 degrees F., and hardening at 1875 to 1925 degrees F. This will result in slightly higher Brinell hardness values.

STAINLESS IRON.

Material of this type is generally used for applications requiring good corrosion resistance, high tensile strength and toughness coupled with ductility. It can be hardened by suitable heat treatment, and is fairly strong and scale resistant at temperatures up to 1400 degrees F.

The typical composition of Stainless iron is as follows: Chromium 11.50—13.50 per cent, Carbon under .12 per cent.

Engineers and those familiar with the difficulties presented in consistently obtaining maximum elastic limit in conjunction with a high Izod value will fully appreciate this steel. Its uses are almost unlimited and it is solving many problems, in valves for high temperature and high pressure service, for valve trim and pump linings in the oil refineries, nitric acid handling equipment, and many other applications.

Too much stress cannot be put on the excellent combinations of physical properties obtainable in this material with the proper heat treatment. Many users, or prospective users, of this type of material have failed to utilize the best properties of the metal and in some instances failures in service have been reported, which were quickly corrected by proper heat treatment.

The free cutting stainless iron variation of the original Stainless Iron has solved many problems in the application of corrosion-resisting steels to parts requiring much machine work, particularly screw machine products. It is possible to procure stainless iron that will not necessitate changing cutting feeds and speeds from those used for ordinary steel.

For parts requiring no special degree of hardness or physical properties, this material should be purchased in the annealed condition.

This brings up the question of obtaining the proper combination of hardness and tensile strength sometimes so necessary in many products. For a time it was thought that in order to use a free machining stainless iron, it was necessary to sacrifice considerable hardness and tensile strength to acquire ease of machining. It is now possible to secure this free machining material either annealed, or heat treated to meet the most exacting specifications, and still utilize the unquestioned advantages of ease of machining. It is being furnished for some applications with a Brinell hardness of 250 with a corresponding tensile strength of 125,000 pounds per square inch, and in this condition is being machined with ease.

We come now to the 18 per cent Chrome 8 per cent Nickel alloy.

While this steel is not a "cure-all" it has properties which make its application possible to a very great extent to products manufactured from sheet or strip. It possesses a high resistance against rupture and a remarkable ductility in the cold state, which makes it capable of being pressed or drawn into a number of intricate shapes. It is extremely tough and will stand drastic deformation without bursting. It shows its deep-drawing qualities best when in the fully softened condition.

At present the largest tonnages of this material are being used in three important industries; automotive, food and oil. The largest use has been in automobiles, although the oil refining industry is a close second, and the food industry is turning to it rapidly. The increased use of this material in 1930 came from its adoption by a large number of users in comparatively small quantities, rather than from large tonnages used by any one industry. In the automotive industry it is being used for radiator shells, headlamps, running board moldings, radiator caps, and bolts subject to severe corroding influences.

In the oil industry it is doing much to solve the difficult problems of corrosion, erosion, and oxidation. It is in constant use in tubular form in cracking still tubes, vapor lines, exchanger tubes, condenser tubes and topping still tubes. In sheet form it has found a ready market in the construction of air preheaters, bubble towers, tanks, and so forth.

The 18 and 8 alloy has come to be known almost universally as KA2 and this symbol will be used in referring to it. It is a chrome nickel alloy containing about 17-20 per cent chromium and 7 to 10 per cent nickel. It is manufactured in two grades according to its carbon content. KA2 contains from .08 to .16 per cent carbon whereas KA2S contains less than .07 per cent. Both alloys attain maximum corrosion resistance only when given a special heat treatment, consisting of heating to above 2000 degrees F. and then cooling quickly, either in water or air. After this treatment they are fully austenitic and non-magnetic. While these alloys cannot be hardened by heat treatment, hot work carried out at fairly low temperatures, around 1500 degrees F., and especially cold work, will harden them considerably, with consequent sacrifice of some ductility.

WELDING.

Arc welds should be made with coated KA2 electrodes. Welding may be done either with alternating current or direct current. With direct current the polarity should be reversed from that in ordinary steel welding practice; that is: the electrodes should be the positive, and the work the negative terminal. The voltage required varies with the thickness of the sheets to be welded and should be as low as practicable, ranging between 40 and 60 volts measured at the welding machine. The current should be between 75 and 125 ampères. On thicknesses of 3/16 inch or lighter, no bevelling of the material at the joint is required. Above 3/16 inch the joint should be bevelled and the material laid in two layers. Where successive layers of material are to be deposited, the weld material of the preceding bead should be allowed to cool thoroughly before the next bead is deposited.

Wherever possible, the metal deposit should be laid down in a continuous stream. Having no capacity for hardening by temperature effects, welds remain tough and ductile and do not develop a coarse, crystalline structure.

In acetylene welding, uncoated rods of KA2 should be used as filler material. Flame should be soft neutral or slightly reducing. The torch should be kept pointed in the direction of the work to preheat the parts to be welded, and the rod should be kept in the flame.

In welding, sufficient heat is induced at or near the welded area to cause carbide precipitation, which lowers resistance to intercrystalline corrosion. Therefore, for maximum resistance to corrosion, all welded parts should be subsequently heat treated, to redissolve these carbides, the temperature consisting of heating to between 2000 degrees F. and 2200 degrees F. and rapidly cooling. If possible, the entire part that has been welded

should be given this treatment; if this is not possible, the part should be made of the low carbon grade (under .7 per cent) as the lower carbon content reduces the carbide precipitation and hence maintains corrosion resistance. Rods of low carbon should be used.

The reference to the above subject made in the instructions on welding deserves a little further explanation. It is most important that this characteristic of KA2 be taken into consideration when contemplating the use of it on work subject to high pressure at high temperatures. KA2 is suitable for applications where temperature does not exceed 600 degrees F. for pressure service.

It has been found that carbide precipitation occurs at high temperatures, which affects both the corrosion resistance and the physical properties of the alloy. This change takes place regardless of previous heat treatment. Therefore it is quite necessary to limit the carbon content to less than .7 per cent when the material is to be used at temperatures above 600 degrees F., under pressure. The low carbon material raises the temperature limit at which this alloy may be used for pressure service to 1300 degrees F.

These figures refer, of course, to the temperature which the metal itself attains. Beyond a metal temperature of 1300 degrees F. neither the high nor low carbon types of this alloy will give satisfactory service for pressure applications.

The foregoing covers in a rather brief manner the outstanding characteristics of the 18 and 8 alloy. There are some variations of the original KA2 type which have lately come into use, designed for particular applications, and containing added elements.

EFFECTS OF ELEMENTS.

The usual carbon content found in stainless steel is .30 per cent and this is considered standard. The useful range of the element, however, is very narrow. Under .25 per cent the steel will not harden successfully for cutlery, while above .40 per cent the steel is difficult to forge and loses considerable of its non-corrosive properties, unless special heat treatments are resorted to. When the carbon is low, .15 per cent or under (stainless iron) the material will not harden sufficiently for a cutting edge. Such a composition forges much easier and this low carbon material is rustless regardless of heat treatment.

Silicon in amounts in excess of .75 per cent raises the critical point, thereby necessitating the use of higher hardening temperatures. It has the advantage, in higher percentages, of producing increased resistance to heat and gives better non-scaling qualities. It does not replace chromium in effecting resistance to stain and corrosion. It has the disadvantage, in high percentages, of increasing tendency to grain growth.

The effect of manganese is very much the same as in carbon steel. It should be kept low although a certain amount is necessary to assist in rolling and hardening.

Sulphur and phosphorous are impurities and as such should be kept as low as possible. They are especially injurious to stainless steel in that they induce electrolytic action which causes corrosion. A modification of the sulphur content is used to produce the free-machining stainless irons.

Chromium is the principal element used in stainless irons and steels. Certain percentages of it in combination with iron render the resultant iron-chromium insoluble in water and many other solutions, so that by heat treatment, if the carbides are diffused through the mass, a metal can be produced which is insoluble and sufficiently homogeneous to remove the possibility of galvanic action.

When nickel is added to a steel it lowers the critical temperature in proportion to the amount induced, until .25 per cent is added, at which stage the critical transformations occur below atmospheric temperatures, therefore a steel of this composition is austenitic. In the presence of chromium, much smaller percentages of nickel are required to induce this austenitic condition.

The presence of copper in stainless steel produces somewhat the same results as does nickel, except that large quantities of it do not render the steel austenitic. It raises the corrosion resistance to certain acids.

Molybdenum has a noticeable effect on the hardness values of stainless steels, raising them to a slight extent. It also aids the corrosion resistance towards some acids.

A typical analysis of the material generally known as Chrome Iron is as follows: Chrome 16.00 to 20.00 per cent, Carbon .12 per cent. This alloy is ductile and easily worked, either hot or cold. It cannot be hardened by heat treatment but can be hardened by cold working at the expense of ductility. It is used a great deal for applications requiring resistance to scaling up to 1500 degrees F., where no great strength or toughness is required. It is also used to some extent in equipment for the manufacture and transportation of the milder organic acids.

It has one very noticeable fault in that it is perhaps the most difficult of all of the stainless types to weld successfully, being subject to abnormal grain growth at welding heats, and the welds cannot be restored to the original structure by heat treatment. It can hardly be recommended for fabrication into welded products where the welds must be relied upon to stand any amount of stress.

It does have the virtue of a very low coefficient of thermal expansion, which renders it very suitable for intermittent high temperature service, due to the fact that it permits of the retention of the protective scale during heating and cooling.

For forging, the proper temperature is about 1800 degrees-1900 degrees F., with a finishing temperature of about 1300 degrees-1400 degrees F. Under no conditions should the finishing forging be done above 1400 degrees F.

Although we have just mentioned that this alloy is virtually unaffected by heat treatment, an anneal after hot or cold working is sometimes advisable for the removal of strains, etc. The correct temperature is 1400 degrees to 1450 degrees F. after hot work, and 1375 degrees-1400 degrees F. after cold working. After hot working, metal should be thoroughly soaked and cooled slowly. After cold working, an air cool will be sufficient.

Special heat resisting is furnished in two general compositions, with two carbon ranges as follows: chrome 20.00—30.00 per cent, carbon .25—.50, or 2.25—2.75 per cent. In the high carbon range it is available in cast form only.

The most general use for this alloy is in furnace parts requiring freedom from excessive oxidation at elevated temperatures, or in furnace atmospheres containing sulphur. It does not have the load capacity at high temperatures possessed by the chrome-nickel 18-8 type. It is extremely useful for making conveyor belts for continuous furnaces, for annealing pans, carburizing boxes, boilers, furnaces, etc.

This brief outline covers the outstanding grades of corrosion and heat resisting alloys in common use today. It by no means touches every detail of the application and fabrication of the metals, but may serve as a guide to users of the product, as well as help them through the rather tangled maze of trade names which, while of value, have in some cases made the intelligent application of the materials rather difficult.—"The Tech Engineering News," April, 1931.

TRENDS IN STEAM-TURBINE DEVELOPMENT.

By A. G. Christie,* Baltimore, Md.

Higher Temperatures and Pressures—Increased Capacities—Improved Materials—Improved Efficiencies Over Wide Load Range—Adjustment of Turbine to Specific Service—Binary-Fluid Turbines.

The present trends of steam-turbine development are toward (a) the use of higher steam temperatures and pressures, (b) increased capacities at the various speeds and increased output from a single casing, (c) the employment of better materials for turbine parts and particularly for blading, (d) higher efficiency over a wide range of load, (e) adjustment of the turbine more closely to the particular requirements of service, and (f) the development of binary fluids for use in turbines. The effect of such tendencies will be the production of larger, more reliable, and more economical turbines than those now available.

HIGHER TEMPERATURES AND PRESSURES.

The possibilities of steam pressures have been determined from the operation of various commercial units to the critical pressure of 3200 pounds per square inch, and the gains from increases of pressure are now fairly well known. Attention has recently been directed to studies of the effect of higher steam temperatures, which conditions present more difficult problems than pressure alone. Metals such as were formerly used in turbine construction develop undesirable properties at temperatures above 750 degrees F. Tensile strength and fatigue limits decrease rapidly at higher temperatures, while the tendency toward that indefinite elongation known as "creep" also increases. The limiting temperature in a steam turbine is therefore fixed by the properties of available metals.

Progress has been made by searching out those materials that may be used safely at the higher temperatures and by designing spindles, blades, casings, etc., to be sufficiently strong under such conditions. "Creep" cannot be entirely overcome. However, parts may be designed so that the working stresses will lead to a rate of creep at the given high temperature which has been considered within safe limits over a period of years. Certain designers have chosen this rate of creep as 0.01 per cent per year, and this or a similar figure may be accepted as a standard rate for high temperatures.

With this rate of creep and with materials now available, turbines can be built for steam temperatures up to 900 degrees F. with assurance of satisfactory operation, while units for 1000 degrees F. can be constructed with every hope of successful operation throughout their useful life.

Methods of supporting casings for high temperature, and provisions for adequate expansion to eliminate causes of deformation in cylinders, are under development.

The application of higher steam temperatures will have a profound influence on future station design. Previously turbines with no reheating were limited to initial steam conditions of 450 pounds per square inch and 750 degrees F. If higher pressures were used with the same temperature, the moisture content at exhaust became excessive. Conservative designers aim

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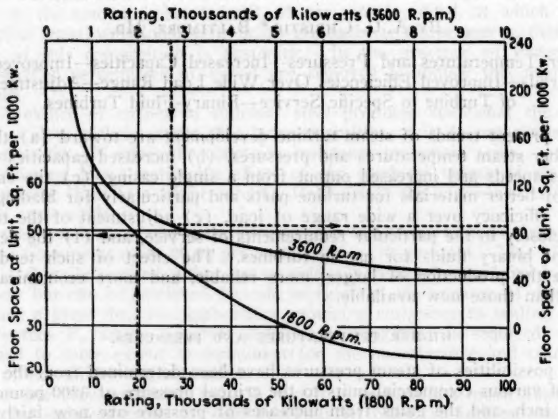
Rating, Thousands of kilowatts (3600 R.p.m.)
0 1 2 3 4 5 6 7 8 9 10
Floor Space of Unit, Sq. Ft. per 1000 Kw.
240 200 160 120 80 40 0
60 50 40 30 20
3600 R.p.m.
1800 R.p.m.
0 10 20 30 40 50 60 70 80 90 100
Rating, Thousands of Kilowatts (1800 R.p.m.)

FIG. 1 FLOOR SPACE REQUIRED FOR SINGLE-CYLINDER 3600-R.P.M. TURBINE ALTERNATORS AND ALSO FOR SINGLE-CYLINDER 1800-R.P.M. UNITS

(This area consists of a rectangle enclosing turbine, generator, and direct-connected exciter, with an added rectangle for any offset valve gear.)

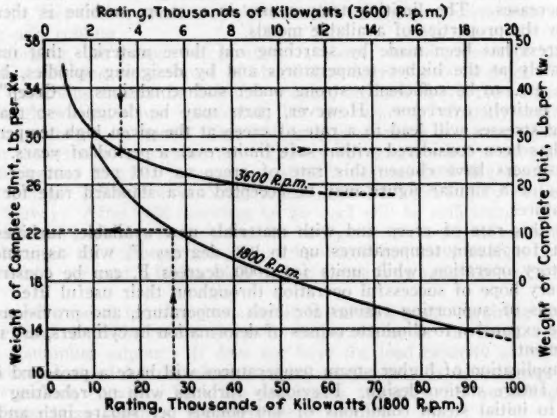
Rating, Thousands of Kilowatts (3600 R.p.m.)
0 2 4 6 8 10 12 14 16 18 20
Weight of Complete Unit, Lb. per Kw.
38 34 30 26 22 18 14 10
50 40 30 20 10 0
3600 R.p.m.
1800 R.p.m.
0 10 20 30 40 50 60 70 80 90 100
Rating, Thousands of Kilowatts (1800 R.p.m.)

FIG. 2 WEIGHTS OF SINGLE-CYLINDER 3600-R.P.M. TURBINE GENERATORS AND OF 1800-R.P.M. UNITS

to keep this moisture content below 12 per cent to prevent erosion in the last blade rows. A single-cylinder turbine of 68,000 kilowatts with no reheating has already been built for 650 pounds per square inch, 825 degrees F. With 900 degrees F. steam temperature, the steam pressure may be raised to 750 pounds per square inch. Hence substantial increases in steam pressure may be expected in future nonreheating turbines when temperatures above 750 degrees F. are employed.

A large number of American stations now use, or will soon use, 1200 to 1400 pounds per square inch steam pressures with steam temperatures of 750 degrees F. and with a single stage of reheating. Steam temperatures of 900 degrees F. may make it economical to increase the steam pressure of reheating stations to 2000 or 2500 pounds per square inch.

Steam conditions in future stations will probably be standardized as follows: with no reheat, 400 pounds per square inch, 750 degrees F. and 700 pounds per square inch, 850 degrees F.; and with one stage of reheat, 1400 pounds per square inch, 750 degrees F. and 2000 to 2500 pounds per square inch, 900 degrees F. In the latter case two stages of reheat may be used if high efficiency is desired.

These considerations apply in general to large central stations. However, the gains from increased temperatures and pressures are equally applicable to industrial plants. When such plants operate without vacuum or exhaust against back pressure into a service main, the proportional gains from using high pressure and high superheat are larger than in condensing central stations.

INCREASED CAPACITIES.

The use of turbines of large rated capacities results in several economic gains. Floor space per kilowatt decreases with increasing size as shown in Figure 1. This results in a smaller turbine room and a lower building cost per kilowatt. Steeple compounding has been introduced to provide a further saving in floor space. Manufacturers are endeavoring to reduce the lengths of their turbo-generator sets to save more floor space. The weight per kilowatt decreases with increased ratings as indicated by Figure 2. Hence foundation costs are lessened. Attention is drawn to the decreased weight of units that operate at 3600 R. P. M. as compared with units of the same rating at 1800 R. P. M. Figure 3 shows that the efficiency also tends to increase with higher turbine capacities, though at a lesser rate in the largest units. First cost per kilowatt (see Figure 4) also decreases with increased capacity. The economic justification for the trend toward higher capacities is evident from a consideration of these data.

Single-cylinder condensing units of 10,000 kilowatts at 3600 R. P. M. have been built in this country. C. A. Parsons & Co. have single-cylinder condensing units of 15,000 kilowatts at 3600 R. P. M. in operation, one at Regina, Saskatchewan, Canada, and are offering similar turbines of 20,000 and 25,000 kilowatts with one casing. The largest unit at 1800 R. P. M. with a single cylinder has a capacity of 80,000 kilowatts. These single-cylinder units of high capacity pass such great volumes of steam through the last row of blades that the leaving losses are large. Such losses tend to offset the gains in engine efficiency which come with increased size. As the result, these large units cannot be expected to establish records of efficiency. However, American engineers favor the single-cylinder units as they decrease station cost and are simpler to operate.

Attention has already been drawn to the large sizes of single-cylinder turbines now available at 3600 R. P. M. Turbines can be built at this

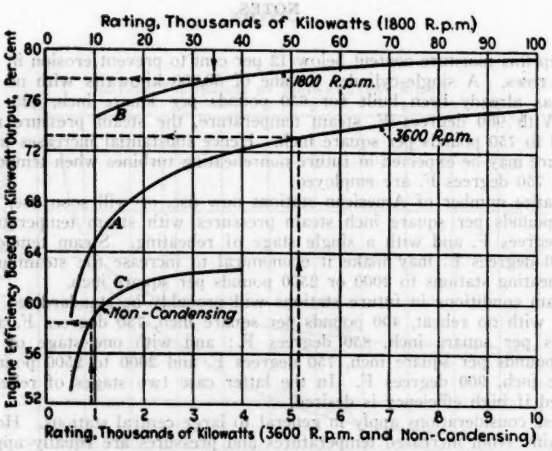
Rating, Thousands of Kilowatts (1800 R.p.m.)
0 10 20 30 40 50 60 70 80 90 100
Engine Efficiency Based on Kilowatt Output, Per Cent
80 76 72 68 64 60 56 52
1800 R.p.m.
B
3600 R.p.m.
A
C
Non-Condensing
0 1 2 3 4 5 6 7 8 9 10
Rating, Thousands of Kilowatts (3600 R.p.m. and Non-Condensing)

Fig. 3 Average Engine Efficiency for the Load Point of Best Efficiency Based on Kilowatt Output at the Generator Terminals

Curve A: Single-cylinder turbines at 3600 r.p.m., for steam conditions up to 300 lb. per sq. in. gage, 600 deg. fahr., 28.5 in. vacuum.
Curve B: 1800-r.p.m. turbines for steam conditions up to 450 lb. per sq. in. gage, 750 deg. fahr., 29 in. vacuum.
Curve C: Non-condensing units for steam conditions up to 250 lb. per sq. in. gage, 550 deg. fahr., atmospheric pressure at exhaust.

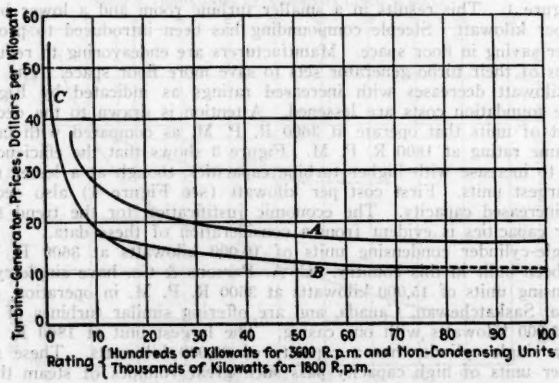
Turbine-Generator Prices, Dollars per Kilowatt
60 50 40 30 20 10 0
C
A
B
0 10 20 30 40 50 60 70 80 90 100
Rating { Hundreds of Kilowatts for 3600 R.p.m. and Non-Condensing Units
Thousands of Kilowatts for 1800 R.p.m.

Fig. 4 Prices for Turbine-Generator Units in the United States

Curve A: 3600-r.p.m. condensing units.
Curve B: 1800-r.p.m. condensing units.
Curve C: Small non-condensing sets.
(Prices include bare turbine and generator without auxiliary generators or direct-connected exciters and are for units delivered and erected. Prices are for pressures up to 400 lb. per sq. in. gage, steam temperatures up to 725 deg. fahr., and, when condensing, up to 29 in. vacuum.)

speed up to 50,000 kilowatts in two tandem cylinders, and up to 100,000 kilowatts when two low-pressure cylinders in tandem are provided. These turbine capacities are beyond the limits of any 3600-R. P. M. generators developed to date. These compound units have certain economic advantages that deserve consideration. Their weight is less than that of a unit of similar capacity at 1800 R. P. M. The shafts are shorter between bearings, and, having less mass, can start under high-temperature conditions more rapidly than units of the same size at 1800 R. P. M. Finally the efficiencies with the same blade speeds and same kilowatt rating are higher in the 3600-R. P. M. than in the 1800-R. P. M. units. These advantages, when more generally recognized, will lead to a wider use of large turbines at 3600 R. P. M.

Multi-cylinder units at 1800 R. P. M. have been built in tandem up to 160,000 kilowatts. Such tandem compound units for large capacities are finding favor among power-plant designers and will be used more extensively in the future. Triple-tandem turbines up to 150,000 kilowatts at 1800 R. P. M. for 1200 pounds per square inch are under construction. Cross-compound turbines with several generators ranging up to 208,000 kilowatts are being used in increasing numbers. The trend in central-station practice is toward the use of larger units, and the capacities mentioned will be exceeded when system loads warrant the increased sizes of turbines.

IMPROVED MATERIALS.

The manufacture of shafts and turbine disks has been improved through better steel-foundry and forgeshop practices, through internal inspection by means of bore holes, through vibrating the disks before assembly, and through careful static and dynamic balancing after completion. As a result of improvements in these practices, troubles with such elements are steadily diminishing.

Many turbine difficulties are traceable to blade troubles. Blade vibration is a common cause of failure. Much research work must still be done to find the proper location of lashing wires, the correct method of silver-soldering these wires, the best form of shrouds, and even the most effective form, size, and angles of the blades themselves to resist vibration in the larger sizes of turbines now used.

Two trends in turbine development have been responsible for much blade trouble. In order to secure added capacity and improved efficiency, blade speeds have been steadily increased until tip speeds of 1150 feet per second are now in use. These operating conditions require long blades of high strength and rigidity. Such blades are liable to vibrate. The second trend is the increasing use of large heat drops at high efficiency, which lead to high moisture contents in the exhaust steam. This moisture causes rapid erosion of the blades in the last rows of the turbine, which not only decreases turbine efficiency but also increases the risk of failure of low-pressure blading and, further, necessitates the replacement of such blades every three to five years. Such replacement is expensive and necessitates a serious outage. Future developments will provide alloy steels for use at these high blade speeds which will have longer life under the wet-steam conditions in the last rows.

Stainless steels at present seem best suited for long blades. A steel with about 12 per cent chromium and 0.1 per cent carbon has given much promise for such service.

Moisture is difficult to remove from this low-pressure steam. Different schemes such as drainage grooves, bypass orifices, etc., have been tried,

but the best results so far reported only indicate the removal of about 25 per cent of the total moisture. A study of eroded blades shows that the destructive moisture is concentrated on the outer half of the blade but not wholly at the periphery. The droplets are undoubtedly of small size and difficult to separate from steam at high velocity. Hence the ineffectiveness of the various catchers and other devices.

The late Professor Goodenough offered the theory that the water droplets travel through the stationary nozzles and blades at a slower speed than the steam, and thus do not enter the blades at the proper relative angle. The faster-traveling steam enters the blades tangentially, as it should, but the slower water droplets are struck by the back of the blade and rapid erosion results. This explains why erosion occurs on the back of the inlet edge of the blade.

Of the various blade materials tried under these conditions, properly heat-treated stainless steels and some nickel alloys seem best. Plating the edges of these blades with erosion-resisting metals has been tried, and heavy plating of chromium appears promising. Sprayed coatings of tantalum, sheaths of Hecla and other metals, coatings of stellite, and nitriding also appear to resist erosion and are being further investigated. There is reason to expect that an erosion-resisting blading may soon be developed.

A suggestion has been made to provide hollow stationary blades or hollow diaphragm partitions in which a hot medium can circulate. The heat from these blades would dry the low-pressure steam passing them. If this can be done, it would not only decrease erosion but would increase turbine efficiency. Turbine builders and users now recognize the seriousness of the problem of properly dealing with this wet exhaust steam. Further research will develop improvements in materials or ways of eliminating the trouble.

Oxidation difficulties in blading have been largely overcome through careful deaeration of feedwater. Some dissociation may later be found in high-temperature superheaters, but its effects are at present hard to predict.

Much trouble has resulted from deposits on turbine blading, and a technique has been developed to remove this in stations where the deposits are troublesome. Purer make-up for boiler feedwater, less condenser leakage, and drier steam from boiler drums to superheaters will do much to overcome this trouble.

IMPROVED EFFICIENCIES OVER WIDE LOAD RANGE.

Efficiency in turbines is largely a matter of price. Each manufacturer offers units which will give about the same efficiency and will sell at about the same price as those of his competitors. Turbines of higher efficiency than these commercial units can be built if one is prepared to pay the higher cost of these improved designs. Load conditions, early supersession by more modern units, changing steam conditions, low fuel costs, and other factors frequently make it uneconomical to purchase a turbine of the highest efficiency. Nevertheless the performance of steam turbines is being steadily bettered, and this improvement will continue.

Large turbines are generally provided with bleeders, and some have reheaters. Hence performance is best expressed in terms of B.t.u. per kilowatt-hour rather than in pounds of steam per kilowatt-hour.

The gains in efficiency from improvements in the design will be comparatively small for any particular feature, but in the aggregate may lead to substantial advances. Efficiencies of 82 to 85 per cent at the coupling are obtained on some American turbines, while an efficiency of 87.7 per cent at the coupling is claimed for a European turbine of 85,000 kilowatts. As

previously stated, the high leaving losses inherent in the design of many turbines of large capacity lead to moderate efficiencies of such units. Better performances may be expected to result from lower leaving losses, from reduction of moisture in exhaust stages, from improved blading in the high-pressure section, and from a greater combination of impulse and reaction effects in all blading. Regarding the latter, there is already a tendency to secure reaction effects from blading on types of turbines which were formerly considered as of the pure impulse type.

Recent designs provide for high efficiency in B.t.u. per kilowatt hour over a wide range of load through the use of secondary, tertiary, and even quaternary inlet valves. This is shown in Figure 5 where the heat consumption of the largest unit does not vary more than 100 B.t.u. per kilowatt-hour from 55,000 kilowatt to 115,000 kilowatt loads. The governor design becomes more complicated when such additional admission valves must be controlled. Manufacturers provide inherent excess capacity in many tur-

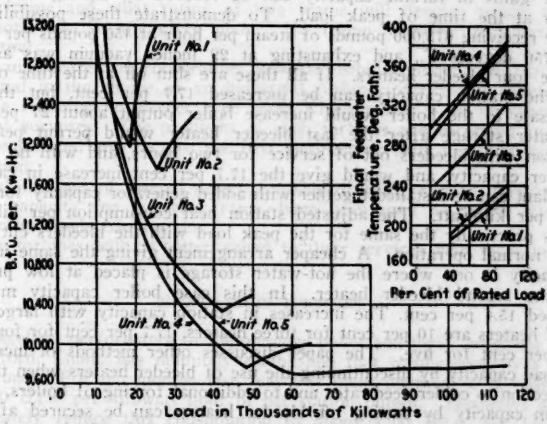

FIG. 5 IMPROVEMENT IN STEAM-TURBINE PERFORMANCE. ECONOMY CHARACTERISTICS OF A SERIES OF FIVE UNITS INSTALLED AND BUILDING FOR A CENTRAL STATION DURING A PERIOD OF EIGHT YEARS

Unit No. 1: 25,000 kw. at 93 per cent power factor. Operating conditions: 350 lb. per sq. in. gage, 675 deg. fahr., 29 in. vacuum, 2-stage bleeding. Installed in 1923.

Unit No. 2: 35,000 kw. at 93 per cent power factor. Operating conditions: 350 lb. per sq. in. gage, 675 deg. fahr., 29 in. vacuum, 2-stage bleeding. Installed in 1925.

Unit No. 3: 50,000 kw. at 85 per cent power factor. Operating conditions: 600 lb. per sq. in. gage, 725 deg. fahr., 29 in. vacuum, 4-stage bleeding. Installed in 1927.

Unit No. 4: 65,000 kw. at 85 per cent power factor. Operating conditions: 600 lb. per sq. in. gage, 725 deg. fahr., 29 in. vacuum, reheat to 725 deg. fahr., 4-stage bleeding. Installed in 1930.

Unit No. 5: 115,000 kw. at 95 per cent power factor. Operating conditions: 625 lb. per sq. in. gage, 750 deg. fahr., 29 in. vacuum, reheat to 750 deg. fahr., 4-stage bleeding. To be installed in 1931.

(From data furnished by Allis-Chalmers Mfg. Co., Milwaukee, Wis. Final feedwater temperatures at various percentages of rated load are also shown.)

bines so that full load can be maintained should boiler pressure drop below normal. But generators are designed with little spare capacity, and if additional overload capacity is desired this must be specified and paid for; or, the generator may be purchased for a lower power factor.

The gains in heat consumption obtained through the use of bleeder heaters have been fully analyzed and discussed and are generally understood by engineers. These bleeder heaters have usually been of the closed type. Successful operation of the high-pressure direct-contact heaters at South Amboy Station may lead to a more extended use of this type.

The last high-pressure heater is frequently furnished with highly superheated steam. It is possible to design a counter-current closed heater to take advantage of this superheat and thus raise the feedwater above the saturation temperature corresponding to the steam pressure in this heater.

Mr. Warren Viessman and the author showed in a recent paper* that, after a turbine has been fully loaded with all bleeders in service, still further gains in turbine capacity can be secured by cutting off bleeder heaters at the time of peak load. To demonstrate these possibilities, a turbine receiving 673,000 pounds of steam per hour at 450 pounds per square inch, 750 degrees F., and exhausting at 29 inches vacuum was assumed to have four bleeder heaters. If all these are shut off at the time of peak load, the station capacity can be increased 17.7 per cent, but the cold condensate to the boiler would increase boiler output about 27 per cent. Hot-water storage after the last bleeder heater would permit peak-load operation with bleeders out of service for two hours, and with no change in boiler capacity, and would give the 17.7 per cent increase in capacity. This plant can be installed together with added generator capacity for about $24.35 per kilowatt. The adjusted station heat consumption per kilowatt-hour is practically the same for the peak load with the bleeders cut off as during normal operation. A cheaper arrangement giving the same increase in capacity is one where the hot-water storage is placed at low pressure after the second bleeder heater. In this case boiler capacity must be increased 15.4 per cent. The increases in station capacity with large numbers of heaters are 10 per cent for three heaters, 17.7 per cent for four, and 21.25 per cent for five. The paper discusses other methods of increasing peak load capacity by discontinuing the use of bleeder heaters when there is no objection to colder feedwater and to additional forcing of boilers. These gains in capacity by cutting off bleeder heaters can be secured after all the gains from other means of overloading have already been obtained. Such methods of providing additional capacity at peak loads can be employed in many present and future central stations.

Reheating of steam is necessary with pressures of 1200 pounds per square inch and above. Flue-gas reheating is apparently gaining ground on account of the marked improvement in station economy achieved by its use. Steam reheating is more convenient in certain stations, but is less economical than gas reheating. The use of diphenyl oxide for reheating purposes is being investigated, and appears to have interesting possibilities.

The use of hydrogen for generator cooling will probably be the next improvement in turbo-generator construction. All experimental units appear to be satisfactory. Fans for circulating the cooling medium—whether air or hydrogen—should be separate from the generator and be designed for variable speed on large units to save auxiliary power at light loads.

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* "Low-Cost Peak-Load Capacity With Bleeder Turbine," by Warren Viessman and A. G. Christie. Presented at a meeting of the Metropolitan Section of the A.S.M.E., January 8, 1931. Published in "Mechanical Engineering," February, 1931, p. 111.

ADJUSTMENT OF TURBINE TO SPECIFIC SERVICE.

The desire to reduce power costs by keeping station investment at a minimum, led to a study of turbine frames and their economic ratings as fixed by their probable use factor throughout their whole operating life, and by the cost of fuel. It is obvious that with low use factors and cheap coal, leaving losses can be increased and the output of a given casing can be greater, thereby reducing first cost, than in the case of a base-load station with expensive coal. Figure 6 from a study by Francis Hodgkinson, of Westinghouse Electric & Manufacturing Co., shows that a casing may have an economical rating from a dollar standpoint ranging from 30,000 to 50,000 kilowatts depending upon the value of K, which is the product of the use factor, expressed as a decimal, and cost in dollars per 1000 pounds of steam. If the most economic installation is to be secured for a given service, it is evident that there must be close cooperation between the manufacturer and the engineers of the purchaser in order to find which turbine frame and what rating of this frame will develop power at the lowest total cost in any given plant. No frame hereafter will have one fixed rating.

The same degree of cooperation between turbine builder and purchaser is essential in the choice of an industrial turbine, particularly where this is of the reducing or bleeder type from which steam is to be taken for industrial purposes. The problems of such turbines are becoming increasingly complicated and require the best engineering skill for their successful solution.

Special turbines of rugged design, capable of being started quickly, and of high capacity for a given frame, have been used as steam stand-by units for hydro-electric systems.

Future turbines will be better suited to their services than those now in use.

BINARY-FLUID TURBINES.

The excellent performance of the mercury boiler and turbo-generator plant at Hartford, Conn., has definitely established that combination as a commercial unit. For ten months last year this plant operated at a heat rate of 10,310 B.t.u. per kilowatt hour of net station output. Engineers expect to ultimately reduce this consumption to about 8500 B.t.u. per kilowatt hour. No data are available regarding initial and operating costs. Consideration must be given to this combination in planning a new plant, particularly if this plant is for a base load or for high use factors.

The success of the mercury turbine will encourage attempts to develop processes to use other materials than mercury such as diphenyl, diphenyl oxide, and zinc ammoniate. Some of these, or others yet untried, may prove suitable for power-plant use.

PROBABLE LIMITING PERFORMANCE.

One will ask, "What is the probable limiting performance to be expected of a steam turbine?" This has not yet been approached, and American economic conditions may never warrant the plant investment to achieve this ultimate end. Probably the best estimate of this limiting performance is that for a large plant with steam at 2500 pounds per square inch and 1000 degrees F., having two stages of reheating to the same temperature, and with six stages of bleeder heating, leading to a station heat rate of about

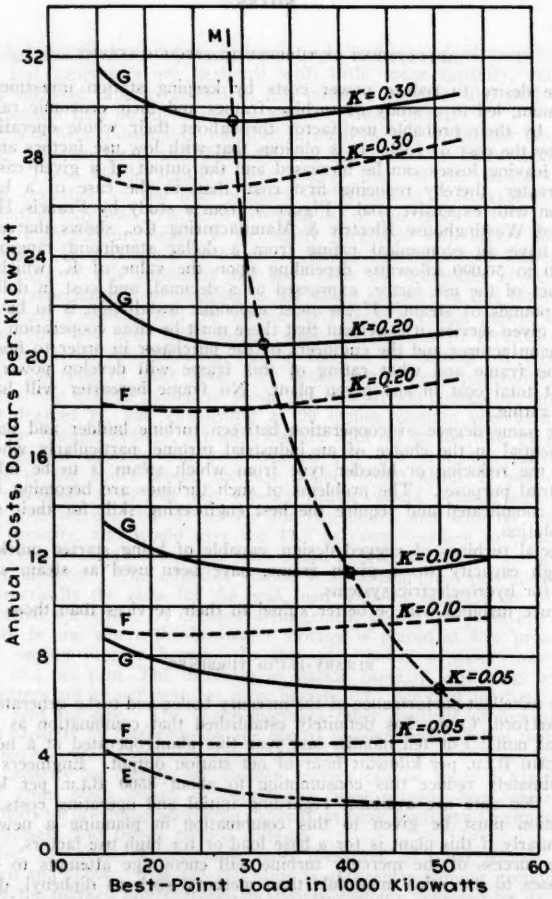

FIG. 6 FIXED CHARGES, ANNUAL OPERATING COSTS, AND TOTAL ANNUAL COSTS FOR TURBINE GENERATOR WITH VARYING USE FACTORS AND STEAM COSTS PLOTTED AGAINST VARIOUS RATINGS. (THIS REACTION TURBINE HAS A LAST-BLADE ANNULUS OF 57 SQ FT.)

Curve E Annual fixed charges in dollars per kilowatt, based on 17 per cent of the first cost of turbine-generator installed and including piping and foundations.

Curves F: Annual operating costs for various values of the product of use factor and costs per 1000 lb. of steam.

(Operating costs are based on the average load carried with an average steam consumption 2½ per cent higher than that calculated for the given load from assumed data. Hence annual operating costs = steam consumption in lb. per kw-hr. at given load as calculated from assumed data ÷ 1000 × 1.025 × cost of steam per 1000 lb. × use factor × 8760.)

Curves G. Total anual costs = Curve E + Curve F for each value of *K*.

Curve M. Loci of minimum values of G curves for various values of *K*.

9500 B.t.u. per kilowatt hour of net output. Within the bounds of our present knowledge, this may be taken as the best performance to be expected of a steam turbine.

With particular reference to the efficiency shown for the non-condensing units, the writer believes this curve must have been based on non-condensing turbines which are not of the latest design or perhaps units which are now obsolete.* Therefore it is felt that the line for non-condensing units should be brought up to date, because a comparison of the efficiencies of condensing and non-condensing turbines as shown by these curves is likely to lead to an erroneous impression as to the relative efficiencies of these two types.

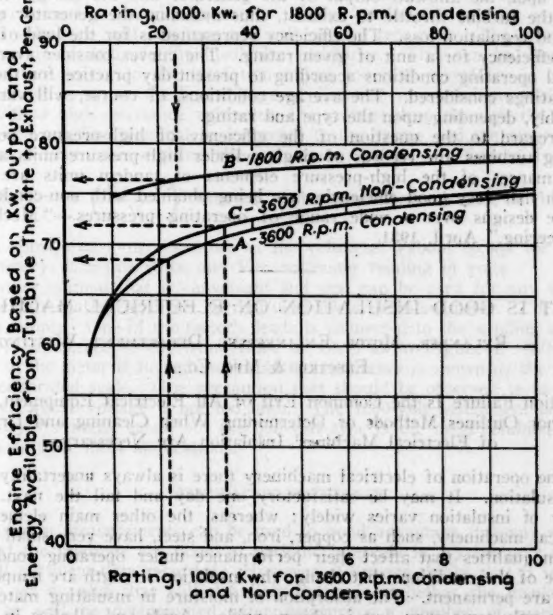

FIG. 7 NORMAL EFFICIENCIES OF STEAM TURBO-GENERATOR UNITS
(Operating conditions according to average of present practice for the various ratings and types.)

As a matter of fact a non-condensing turbine of comparable design will average a little better in efficiency than the same rating of condensing unit.

There are obvious reasons for the better efficiency in the non-condensing turbine. Considering normal operating conditions, the non-condensing unit does a much greater percentage of its work in the superheat field as com-

* Discussion contributed by R. T. Luce, Steam Turbine Department, Allis-Chalmers Manufacturing Company, Wilwaukee, Wis.

pared to the condensing turbine. Due mainly to the comparatively short heat drop, and the resulting larger quantities of steam used, the physical proportions of the non-condensing turbine for a given rating are favorable. The turbine shaft can be of comparatively large diameter with good blade heights, resulting in a rugged design with good leakage characteristics. Due also to the short heat drop, ideal conditions of velocity ratio are more easily attainable, and because of the small specific volume at exhaust, leaving-loss difficulties are reduced to a minimum.

Figure 7 shows the normal efficiencies of turbo-generator units for the three types considered, and it is believed that this graph represents the present practice, especially when considering the comparative efficiencies of the three types. The efficiency is expresed as the Rankine-cycle efficiency ratio based upon the kilowatt output of the generator and the energy available from the turbine throttle to exhaust, thus including the generator efficiencies and regulation loss. The efficiency represented is for the load of maximum efficiency for a unit of given rating. The curves consider average or normal operating conditions according to present-day practice for the types and ratings considered. The average conditions, of course, will vary considerably, depending upon the type and rating.

In regard to the question of the efficiency of high-pressure non-condensing turbines, the records of single-cylinder high-pressure units and the performances of the high-pressure elements of tandem units are proof enough that very good efficiencies are being obtained with non-condensing-turbine designs over a wide range of operating pressures.—"Mechanical Engineering," April, 1931.

WHAT IS GOOD INSULATION ON ELECTRICAL MACHINES?

By J. L. Rylander, Motor Engineering Department Westinghouse Electric & Mfg. Co.

Insulation Failure Is the Common Evil of All Electrical Equipment. The Author Outlines Methods of Determining When Cleaning and Drying of Electrical Machines' Insulation Are Necessary.

In the operation of electrical machinery there is always uncertainty about the insulation. It may be satisfactory one day and fail the next. The quality of insulation varies widely; whereas, the other main elements of electrical machinery, such as copper, iron, and steel, have very small variations in qualities that affect their performance under operating conditions.

Some of the conditions that change the insulation strength are temporary; others are permanent. The absorption of moisture in insulating material is usually only temporary, but is objectionable. Acids and alkalies in liquid form are even worse than ordinary moisture.

Many machines have parts, such as commutators and collectors, which cannot be inclosed in solid insulation. Where air is the insulation between live parts or to ground, an accumulation of conducting dust may bridge across the air spaces and short circuit the insulator. It is not necessary that a motor operate where the surrounding atmosphere contains conducting material to cause a condition dangerous to commutator and collector-ring insulation, because dust worn from the machines' brushes and commutator or collector rings is conducting material. Any machine with excessive brush wear needs attention and observation to guard against insulation breakdown.

The deteriorating influences previously mentioned are nearly always pres-

ent to some extent in electrical machines. The gathering of dust is to a considerable degree a cumulative process. Some of the dust penetrates into crevices that cannot be blown out and some becomes embedded in the varnish surfaces. The absorption of moisture may occur when a motor stands idle for a day or more in a damp location. When a motor or generator is in this condition the operator may well hesitate about starting it up and consider if he should dry out the windings. To dry out a winding means expense, trouble and a loss of time. On the other hand, if the winding is not dried out it may fail when starting up or shortly afterward. For this reason it is desirable to have some means of helping to decide whether the insulation is in satisfactory condition for operation.

There are two common methods of testing insulation. One is to apply a given voltage to see if the insulation has sufficient dielectric strength. This practice has one disadvantage. If the insulation does not stand the applied voltage it will puncture and will require repairing. The other common test is to measure the insulation resistance. This can be done with comparative safety to the insulation unless too high a voltage is applied. One method is to use the line voltage of direct-current machines and measure, with a high-resistance voltmeter, the voltage drop through the insulation when one line terminal is connected to the frame and the other to the winding. From this reading the insulation resistance is figured from the formula $R = r\left(\frac{E - V}{V}\right)$ where R = the insulation resistance of the winding in ohms, r = ohms resistance of the voltmeter (about 60,000 for a 600-volt meter), E = line volts, and V = voltmeter reading in volts.

Another method that is convenient and that can be used for any winding whether alternating or direct current is to use a megohm meter. The operation is simple. One of the meter's leads is connected to the winding and the other is connected to the iron frame or core, as in Figure 1. When the crank of the meter is turned the insulation resistance is shown by the pointer on a calibrated scale. One precaution that should be observed is to choose a meter whose voltage is not too high. The 1000-volt instrument is unsatisfactory for many cases, but the 500-volt type is the most commonly used and is best for most applications.

INSULATION RESISTANCE.

Insulation measurements can be used to good advantage in many applications if the readings are taken at periodic intervals in a systematic manner and all pertinent data recorded. However, if anyone thinks that it is possible to set a value that will definitely determine whether the insulation is safe, he will be disappointed after measuring a number of machine at different times. Duplicate machines will often show no similarity in regard to insulation resistance. The curves A, B and C in Figure 3 show the probable reason.

Every machine will have insulation resistance values that vary from very low to very high if one measurement is made when the insulation is saturated with moisture and other measurements taken after the insulation is dried out. An induction motor having 100,000,000 ohms insulation resistance when thoroughly dry may have as low as 10,000 ohms when saturated with moisture. An armature will show similar change in resistance values if the insulation creepage surfaces on the commutator become embedded with carbon dust in the varnish surface even when a small amount of mois-

ture is present. Furthermore, some motors will operate satisfactorily when the insulation has absorbed considerable moisture, whereas others will fail because of a much smaller quantity.

The type of insulation, the voltage stress and its dielectric strength are determining factors on how much moisture a winding may absorb before it will probably fail. Some materials may show a high insulation resistance and have a low dielectric strength, while others will have a relatively low insulation resistance and a good dielectric strength. Dielectric strength is the more important quality.

To show the difficulties of setting an insulation value as being the dividing line between what is safe and what will fail, the records on three machines are given: A 5-horsepower, 220-volt motor that had already failed by grounding had no dielectric strength, but had an insulation resistance of 125,000 ohms. A 25-horsepower, 440-volt motor was sprayed with water at regular intervals, and its resistance would get as low as 10,000 ohms, yet it did not break down at normal voltage. A large motor failed that had an insulation resistance of 4,000,000 ohms at the time of failure. The failure occurred in the coil ends, not in the slot.

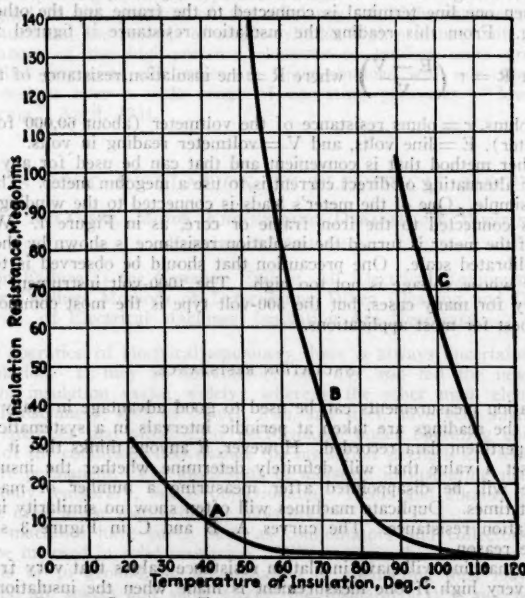

FIG. 3.—CURVES SHOWING EFFECTS OF TEMPERATURE ON INSULATION.

Curve *A* is for insulation that has considerable volatile matter. Curve *B* is for insulation containing an average amount of volatile matter. Curve *C* is for insulation in which there is very little volatile matter. It is evident from these curves that the amount of volatile matter in insulating materials has a marked effect upon its resistance with changes of temperature. Materials high in volatile matter have low resistance at low initial temperatures, where low-volatile materials have high insulation resistance at low temperatures. The insulation resistance of all three shows a decided tendency to decrease as the temperature is increased.

MAKING INSULATION-RESISTANCE TEST WITH A VOLTMETER OF KNOWN RESISTANCE.

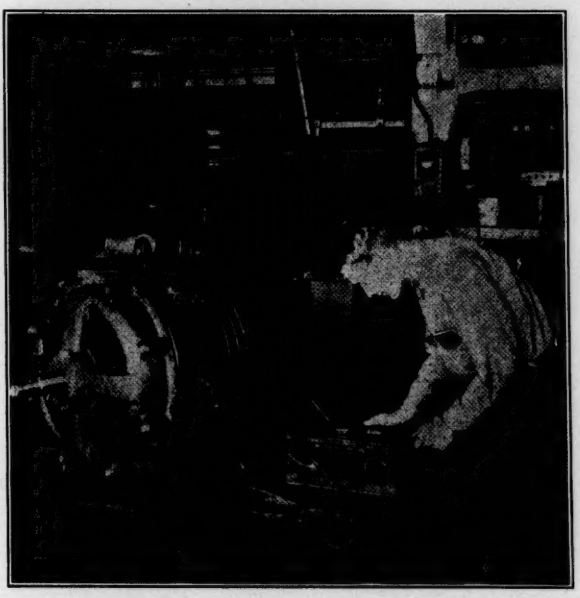

FIG. 1.—INSULATION-RESISTANCE TEST BEING MADE WITH A MEGOHM METER.

FIG. 2.—APPLYING A HIGH-POTENTIAL TEST TO AN INDUCTION MOTOR'S STATOR WINDING.

Insulation-resistance measurements are valuable in determining the presence of moisture and conducting materials. Nevertheless, these measurements do not definitely indicate whether the insulation will stand up or fail if the machine is operated. Tables I and II show the effect of moisture on insulation resistance of two motors which had been intentionally sprayed with water.

TABLE I.—INSULATION RESISTANCE OF A 5-HORSEPOWER, 220-VOLT INDUCTION MOTOR.

	Ohms
At 20 degrees C., winding dry	100,000,000
At 20 degrees C., after 1/2 hour spraying with water	30,000,000
At 70 degrees C., after 2-1/2-hours run	56,000
At 70 degrees C., sprayed while hot, stood idle all night, then run 2-1/2 hours	20,000

TABLE II.—INSULATION RESISTANCE OF A 7-1/2 HORSEPOWER, 230-VOLT DIRECT-CURRENT MOTOR.

	Ohms
At 20 degrees C., winding dry	19,000,000
At 20 degrees C., one hour after spraying with water	10,000
At 70 degrees C., after above spraying and running at full load for four hours	1,750,000

Table III gives the values of insulation resistance on a number of machines of different sizes, different voltages, and of various types.

THE EFFECT OF MOISTURE.

When motors stand idle they absorb moisture. The insulation resistance decreases rapidly when the insulation absorbs even a small amount of moisture. The quantity of moisture absorbed depends upon the humidity of the air, the length of time, the kind of insulation, and whether it is sealed with varnish. Figure 4 shows the effect of relative humidity and time.

All insulating materials absorb moisture. This is contrary to the common belief that varnish coatings are absolutely moisture proof. Of all the insulating materials, mica splittings are least affected by moisture. Varnish coatings absorb moisture and also allow moisture to penetrate through them, but the quantity and rate of penetration are slow compared to most materials that are untreated. The rate of absorption of moisture in untreated cotton tapes or papers is hundreds of times faster than in a varnish film. The untreated materials will become filled with moisture in a few seconds like a blotter absorbs ink. A varnish film will require from a week to a month to become saturated with moisture, and even then the amount is small compared to untreated material. This great difference accounts for the almost universal practice of treating all absorbent insulation materials with varnish or other impregnating compounds.

When motors are used in damp locations and stand idle for days a sufficient amount of moisture may penetrate the windings, sealed with coats of varnish, to cause the insulation to fail. The heavier the coat of varnish the longer it takes for moisture to penetrate it. This, however, is not always an advantage. For example, if a motor with its windings covered with heavy coats of varnish stands idle in a damp place for a month it will have absorbed considerable moisture. When the motor is started the moisture cannot be driven off except with great difficulty. This entrapped

moisture may or may not cause failure, depending on a number of factors, such as the type of insulating materials, their quantity, the voltage stress on them, and also the voltage stress and insulation in the winding between adjacent turns.

Table IV shows the insulation resistance of a 5-horsepower induction motor which had absorbed considerable moisture and that was sealed in by adding two coats of baking varnish. It will be noticed that long continued baking did not drive out all of the moisture. The windings were dried continuously for five days at 105 degrees C.

THE EFFECT OF TEMPERATURE.

Temperature has a considerable effect on insulation resistance and is second only to moisture in causing a change in its values. Other things being equal, insulation resistance decreases as the temperature increases. This can be seen by referring to Table III. The general effect is shown

TABLE III.—INSULATION VALUES OF DIFFERENT TYPES OF ELECTRICAL MACHINES AS DETERMINED BY TESTS.

Horse-power	Kind of Machine (New and Dry) Volts	Type	Insulation Resistance in Megohms Stator 20°C	Stator Hot	Rotor 20°C	Rotor Hot
1	220/440	Ind. motor	100	5	.....	.....
2	220/440	Ind. motor	100	5	.....	.....
3	220/440	Ind. motor	100	5	.....	.....
10	220/440	Ind. motor	100	5	.....	.....
15	220/440	Ind. motor	100	5	.....	.....
350	550	Ind. motor	O.C.*	50	O.C.	100
125	2,200	Ind. motor	O.C.	100	.....	17
200	4,150	Ind. motor	O.C.	.....	40	.....
250	6,300	Ind. motor	O.C.	.....	35	.....
1,500	6,600	Ind. motor	.....	50	.....	6
3,500	6,600	Ind. motor	100	85	8	0.8
4,000	6,600	Ind. motor	75	25	O.C.	50
6,250	480	Syn. motor	O.C.	20	100	50
350	2,300	Syn. motor	O.C.	75	100	50
2,500	2,200	Syn. motor	100	.....	100	.....
5,000	4,000	Syn. motor	O.C.	40	20	0.4
800	6,600	Syn. motor	O.C.	100	100	60
2,000	6,600	Syn. motor	100	45	10	1.5
2,100	6,600	Syn. motor	O.C.	.....	100	.....
5,000	6,600	Syn. motor	O.C.	100	15	4
5,760	6,600	Syn. motor	O.C.	20	15	1.5
13,620	6,600	Syn. motor	O.C.	13	15	0.05
18,750	13,000	Tur. gen.	100	50	50	20
450	550	D.-C. gen.	100	8	12	0.18
450	550	D.-C. gen.	100	40	19	8
35	600	Rwy. arm.	.....	.....	100	3
300	480	Rotary conv.	O.C.	75	100	25

* Very high insulation resistance as indicated by infinity calibration on the meter's scale.

in Figure 3. It is apparent that when insulation resistance values are recorded or discussed the approximate temperature of the winding should always be given.

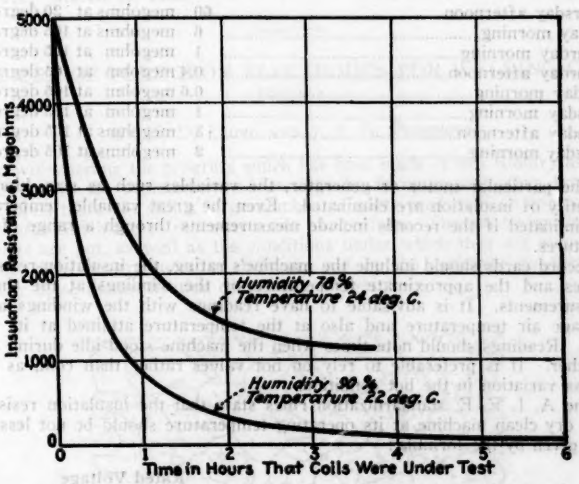

FIG. 4.—EFFECTS OF HUMIDITY ON INSULATION RESISTANCE OF ARMATURE COILS WITH MICA INSULATION.

As a machine increases in physical size, the insulation resistance decreases, on account of the greater area of conducting surface. Likewise, an individual armature coil or small piece of insulation has an insulation resistance that is many times that of a complete winding. Also, as the thickness of insulation increases, as in high-voltage machines, the insulation resistance increases accordingly. If a winding is connected to parts, like commutators, collectors, connectors, or ventilated coils, where there is exposed copper, the insulation resistance will be much less than when the parts are completely covered with insulation. The insulation resistance of exposed parts is usually controlled by the surface creepage from the exposed copper to the nearest iron. Here a small amount of moisture has a large effect. If there is an accumulation of dust the effect is even greater. When both moisture and conducting dust are present the moisture bridges across from particle to particle and causes the resistance to be so low as to be dangerous to the insulation.

USING INSULATION RESISTANCE AS A GUIDE.

To use resistance as a guide to the condition of electrical-apparatus insulation it is necessary to know what its insulation resistance is under a given set of conditions. If comparable data are available from previous readings

TABLE IV.—INSULATION RESISTANCE OF A MOTOR IN WHICH MOISTURE WAS SEALED IN WITH VARNISH.

Time	Insulation Resistance
Thursday afternoon	60 megohms at 20 degrees C.
Friday morning	6 megohms at 105 degrees C.
Saturday morning	1 megohm at 105 degrees C.
Saturday afternoon	0.4 megohm at 105 degrees C.
Sunday morning	0.6 megohm at 105 degrees C.
Monday morning	1 megohm at 105 degrees C.
Monday afternoon	3 megohms at 105 degrees C.
Tuesday morning	2 megohms at 105 degrees C.

on the particular motor or generator, the variables such as size, kind and quantity of insulation are eliminated. Even the great variable, temperature, is eliminated if the records include measurements through a range of temperatures.

Record cards should include the machine's rating, the insulation-resistance values and the approximate temperature of the windings at the time of measurements. It is advisable to have readings with the windings at the average air temperature and also at the temperature attained at its usual load. Readings should note times when the machine stood idle during damp weather. It is preferable to rely on hot values rather than cold, as there is less variation in the hot condition.

The A. I. E. E. standardization rules state that the insulation resistance of a dry clean machine at its operating temperature should be not less than that given by the formula:

$$\text{Insulation Resistance in Megohms} = \frac{\text{Rated Voltage}}{\text{Rating in kva.} + 1000}$$

It should be noted that this is for dry machines at their operating temperature. No definite rule can be set for machines whose insulation is not dry or nearly so. Motors operating in damp locations will have much lower values than those determined by the above formula, but, as mentioned previously, machines may fail which have much higher values than these.

THE ROAD TO SAFETY.

Insulation-resistance measurements can be likened to the signs along a highway. These signs show the condition of the road, but do not tell which automobiles can proceed safely and whether they have to put on tire chains to do so. Putting on tire chains would correspond to the limited drying out of the insulation. Just as the condition of the tires, the length of wheel base, and other factors make one automobile act differently from others, so does the general design of the winding and the insulation, and the safety factor allow one winding to operate satisfactorily and another to fail under the same moisture conditions.

It is evident that insulation-resistance measurements will always record the presence of moisture in insulation and give an idea of its magnitude, and also record the presence of excessive conducting dust on the windings. However, insulation resistance does not determine the dielectric strength of the insulation, although in gneral the dielectric strength increases with increase in resistance and decreases with decrease in resistance. From the advantages mentioned, checking the condition of the insulation at regular periods

and in emergency conditions should prove a decided advantage. Fortunately modern insulation has been so developed and protected by varnish and other treatments that relatively few breakdowns occur under normal conditions.—"Power," March 17, 1931.

THE USE OF PURE IRON ELECTRODES FOR WELDING CAST IRON.*

By H. D. Lloyd and J. S. G. Primrose.

Notwithstanding the progress which has been made in this country as well as abroad in the replacement of castings by forgings and other types of structures, there are still a large number of parts used daily in engineering structures which are of necessity made of cast iron. The use to which these castings are put, as well as the conditions under which they are made, frequently lead to fractures or failures, and in the endeavor to mend or remedy these the application of welding is useful.

Photomicrograph of Soft Pure Iron, Annealed. 100 Per Cent Ferrite, Magnified 100 Diameters.

* Abstract of paper recently presented to the Institution of Welding Engineers.

When it is considered what a complex and heterogeneous group of metals is covered by the generic term "cast iron," it is not surprising that difficulties are often met with, not only in producing sound castings, but, further, in making sure that any kind of welding treatment will be satisfactory in making good damage or defects. It was soon obvious that what is known as ordinary smith's welding is quite impossible with cast iron, on account of the large percentage of elements present making the iron base crystals brittle instead of malleable, and at the same time unable to adhere by a process of intercrystallization such as occurs in the welding of pure soft iron.

The cast iron must be raised to fusion temperature before any joining of the metal can take place, and such drastic heating involves the melting of at least the surface of the metal. In the case of common phosphoric irons there may be a certain amount of liquidation of the more easily fusible parts to give an irregular and therefore better holding surface to the added metal, but there is always the disadvantage that the comparatively cold mass of the unmelted iron causes a rapid freezing of the weld metal; and this accelerated cooling produces a hard part, usually at the junction of the work and the weld, due to the retention of the dissolved carbon in the combined or white condition. Whilst the weld metal may itself be comparatively soft, the hard junction layer is practically unmachinable, and this constitutes one of the great difficulties of welding cast iron in such a way as to be of use to the engineer desirous of using it.

A considerable degree of success has now, however, been attained, both in the methods of recovering waster castings and of repairing breakages in service, if need be in position; and in most cases such an operation can be guaranteed to give as much soundness as the original castings themselves. The chief methods of attaining this object involve the use of a very soft iron, or sometimes a very low carbon cast-iron, filling rod, but it is largely due to manipulation that it is possible to minimize the hard rim and get a machinable weld. One of the earliest methods which give a fair amount of success made use of the oxy-acetylene blowpipe for simply melting into the cavity or join to be filled, a rod of suitable composition preferably covered with a flux to enable a clean bath of metal to be maintained in the weld. Whilst pure iron wire can be used for this purpose under suitable conditions, this type of welding has generally been practiced with filling rods of special cast iron containing as much as 5 per cent of silicon to ensure that when the weld solidifies as much as possible of the carbon will be precipitated as graphite, and very little left in the hard, combined condition. To get rid of the chilled edge in this case it is almost a necessity that the whole casting should be preheated; and when success has attended the actual welding operation there is often a great danger of the casting failing again, not at the weld even when it is perfectly sound, but just outside of the weld area at a short distance away from it, where there has been formed, due to the extreme heating effect produced, a layer of altered graphite which is known from practical tests carried out on a wide range of test bars to lower the transverse breaking strength and the tensile strength of the cast iron by as much as 15 per cent, and sometimes 20 per cent from that of the original cast structure. There is also the danger of considerable distortion taking place in large or intricate castings when they come to be preheated prior to welding, and if sufficiently slow cooling is not achieved, which also serves to remove many of the internal stresses left in the casting, then subsequent annealing may have to be resorted to, and this further acts detrimentally on most types of cast iron.

What really amounts to a welding process is occasionally practiced in the foundry when a broken or defective part is mended by what is known as

"burning-on" with molten cast iron poured from a ladle. In this case the part affected is made to form one side of an open mold, the shape of the required addition being molded in sand around it. The heat of the molten iron poured through the open mold raises the exposed face of the solid metal to fusion heat, and when this is attained the outlet from the mold is stopped,the space filled up with a sufficient head of molten metal, and the whole allowed to cool slowly in sand. With moderate care this method is remarkably successful, and is capable of producing in skilled hands a joining of two separate parts which will not break in the weld, generally due to a finer graphite and grain size existing there; and, further, there is almost no appreciable weakening of the adjacent iron, since the heat is not nearly so great or so intense as the oxy-acetylene flame, and hence there is not the same chance of the surrounding graphite being altered and weakened.

A similar method of welding cast iron which does not necessitate the transportation of the broken casting to the foundry floor is the thermit process, in which the heating of metal is brought about by the intense evolution of heat by the alumino-thermic reaction, whereby the powdered aluminium oxidizes at the expense of the iron oxides present, with the production of a small bath of highly superheated iron. This is generally prepared in a small specially lined crucible immediately above the cavity to be filled, and on raising the stopper the fluid metal runs into the cavity, and before solidifying raises the surface to a fusion heat, when intercrystallizing takes place during the subsequent cooling.

The greatest advance was made when electricity was first employed for producing the necessary localized heat for welding cast iron, only the carbon electrodes at first used not only fused the cast iron filling rods in order to melt them into the weld, but there was a considerable tendency to carburize the added metal; and even when preheating was used to aid slow cooling of the weld, the hard region in the fusion zone was generally too hard to machine, and this rendered the method expensive as well as troublesome.

Recently the most promising methods of operation involve the use of the metallic arc, in which case the electrode itself acts as the filling rod and conveys the necessary current to melt the added metal, which is best laid down in the deposit of the weld in short runs, so that heating is localized to the greatest possible extent, and deleterious effects upon the surrounding iron are reduced to an absolute minimum. In this method of operation it is not advantageous to preheat the casting, and in fact for moderately large jobs it is best dispensed with, since, apart from the trouble of preheating uniformly, there is always the risk of serious distortion which may not be easily rectified.

In most cases no matter whether only a small patch is needed or quite an extensive addition is being made to a badly eroded part, or even, in extreme cases, where a considerable portion has dropped out, the best filling rod to use is one of soft iron of the greatest purity, as even mild steel of ordinary quality contains quite appreciable quantities of impurities which act detrimentally to the necessary changes which take place in laying down successive layers of weld metal. In this connection it may be well to note the growing tendency to employ bare-wire electrodes, and without any surrounding atmosphere of neutral or reducing gas, expect to find a perfectly sound weld made in an oxidizing atmosphere. Not only is there a considerable proportion of oxide formed and dissolved in the weld metal as it melts and precipitates itself across the arc space, but at the high arc temperatures the nitrogen from the air actively unites with the iron when it is unprotected by a fusible coating, which ought to be there to form a protec-

tive flux. The presence of iron nitride in such welds made with bare wire is inevitable, and as such nitride hardening produces unmachinable spots, its use and presence cannot be too strongly deprecated.

The great advantage of using pure soft iron must be obvious, not only from a metallurgical but also from a practical point of view, always provided that it is coated with a suitable flux which will act not only as a protective to the fine particles of highly superheated metal which are shot across the arc space into the cavity to be welded, but also ensures a very useful covering to the bath of molten metal laid down on the surface being covered. The adhesion of the added metal to the cast iron is perfect, due in part to the high absorptive powers of the pure iron for carbon when in the highly heated molten state, and thus a considerable dilution of the carbon content takes place at the actual junction of the work and the weld metal. By making short runs it is quite easy to see that any slight chilling effect of the mass of the casting upon the first layer of the added metal is perfectly removed by annealing when the second and subsequent layers of weld metal are run over the first. The whole heating effect is so strictly localized that no considerable contraction stresses are set up in the surrounding parts of the casting, or even upon the weld metal itself, but the latter being of such pure soft metal will stand a certain amount of distortion without fracturing or even putting undue stress upon the metal in the casting. In this way, with but ordinary care, it is possible to lay down a thoroughly sound and strong weld which has not materially harmed the original iron, and produced a join which is readily machinable, without the trouble of either preheating or subsequent annealing.

As a practical example, details may be given of the successful welding up of the large gas-engine bedplate which failed due to a crack developing in the water-jacket end and extending almost 10 feet along the bottom of the bed. Replacement would have involved both considerable cost and delay, and the repair was effected easily in a very short time by means of a double V weld made with pure soft iron. Photographs taken of both sides of the finished repair indicate the extensive nature of the welding operation. No preheating was employed, and very light runs were taken to cover the join in successive layers of five and even six thicknesses. In the middle of one machined face the cast iron part had completely broken out, and a new part had to be cast to its shape, and was actually welded in near the middle of the crack. Only on this position was it found advisable to make a top run of a non-ferrous metal filling rod to finish the weld before machining in order to get the smoothest possible surface. Another instance concerned a flywheel in which one of the radial arms had cracked near the rim; and after two successive attempts at welding, which only resulted in a further portion cracking away when the rim cooled, the built-in portion was successfully joined by the aid of pure soft iron, and continued to do active service for many years. Numerous cases can also be cited of slight cracks in water-jacketed cylinders, which were satisfactorily welded up with pure iron electrodes, and no trouble was experienced in lapping them out to the correct size.

When occasion demands that the added metal shall be for certain purposes of practically the same composition as the cast iron to which it is welded, then instead of attempting to get a cast iron filling rod of such different composition that after it has suffered oxidation losses in the metallic arc it will be approximately the same as the casting, it is often preferable to start with a pure iron electrode, and by means of suitably adjusting the flux-coating, to deposit a synthetic cast iron in the weld which will be free from sulphur and phosphorus contaminations, both being hardeners.

Manganese, in the form of its dioxide, is therefore a most useful constituent of the flux coating, and generally plays an even more important part in protecting the pure iron from oxidation and nitriding than any easily reducible silicon-carrier used for softening the weld metal. By these means it is possible to produce a weld metal in which the free graphite is in a very small and uniform condition, and a minimum amount of combined carbon is present, but there is still the difficulty of getting somewhat harder weld metal at the junction with the work, and a risk of finding this too hard to machine. Alternative methods which have been used include the electrode metal of 1 per cent carbon steel, and even with up to 20 per cent of nickel addition, but in these cases again the Brinell hardness value of the weld addition often exceeds 300 kilograms per square millimeter under the 10 millimeter ball and 3000 kilograms loading, and when that is so there is generally trouble in machining.

An interesting point which is often overlooked when welding repairs have to be done on cast-iron parts, is that in regard to the size of the graphite flakes which have separated out in the casting. When these are comparatively large and plate-like in their flaky formation, then there is usually considerable trouble in making a good weld, and this is no doubt partly due to the difficulty of getting a clean metal foundation for the added metal, and also to the formation of carbon dioxide gas from the oxidation of the exposed flakes under the heating action of the arc. Much more satisfactory work can be quite easily accomplished with the modern form of low silicon irons of the pearlitic variety, in which the ground-mass has practically no free silicon-ferrite, and the graphite particles are in the finest and most readily soluble form possible.

One of the most difficult varieties of cast iron to weld is that known as white-heart malleable. When ordinary steel electrodes are used there is usually formed a rim of white iron near the junction of the weld metal and the casting, and to obviate this it has been usual to employ a non-ferrous filling wire such as Tobin bronze, which is low in tin content. Whilst this may be satisfactory for many purposes, the presence of the non-ferrous metal frequently leads to active corrosion being set up, and where this has to be guarded against, then the remedy is the use of a soft pure iron which minimizes both this trouble and the amount of hard layer between it and the metal of the casting. Much less trouble is involved in the welding of the black-heart variety of malleable cast iron, since the amount of carbon contained in this, although often greater than in white heart, is practically all in the free amorphous graphitic state. This iron is very much more ductile than the white-heart variety, and therefore more readily bends than breaks, so that it is not often that fractures occur and require to be mended.

Use of non-ferrous metal filling rods is chiefly found to be of advantage in such cases as the castings consisting of very thin or very hard iron, and any iron filling would set up such stresses as would probably lead to spontaneous fracture of the casting as it cooled. Apart from the Tobin bronze mentioned above, two of the most common alloys used are phosphor bronze and the copper-nickel composition known as monel metal. Even if not used entirely to fill the welded join, the latter can be very advantageously employed in making a final run on the top of a series of soft pure iron runs on places where extensive additions of weld metal have been made, and where specially smooth finish is required in the machining operation.

It has recently been suggested that a very good method of testing the service ability of a weld is to ascertain the forging features of the weld metal itself. In this connection a word of warning may be given in regard to thus testing the forging properties of a pure soft iron weld, since it

differs from mild steel similarly deposited. Thus, whilst there is a critical working range in mild steel between 350 degrees and 450 degrees C., in which bending, etc., is not practicable, similarly in the pure soft iron there is a working temperature range in which it is not malleable. This range extends from 900 degrees to 1000 degrees C., between which temperatures welds should not be bent or hammered, but either above or below this the weld metal will satisfactorily withstand the severest punishment without loss of malleability.

TABLE OF SOFT IRON AND STEEL ELECTRODES.

Analysis.	S./M. Amer.	S./M. Brit.	S./M. Cont.	Thomas Cont.	Swed. Chilled Steel.	Swed. Chilled Iron.	Pure Soft Iron.
Carbon	0.12	0.10	0.09	0.08	0.10	0.09	0.013
Silicon	0.03	0.09	0.02	0.04	0.03	0.02	trace
Sulphur	0.04	0.02	0.03	0.045	0.025	0.033	0.027
Phosphorus	0.03	0.02	0.03	0.08	0.01	0.04	0.12
Manganese	0.52	0.42	0.35	0.35	0.28	trace	0.034
Copper	trace	0.025	0.015	trace	trace	trace	0.033
Tensile stress	28	27	28	32	26	25	22
Elongation	15	24	22	18	25	27	30

In conclusion, it must be admitted that the successful welding of cast iron is not always an easy matter, as much depends upon the skill and experience of the operator, and the type of rod preferred by one will not always suit another. Each individual case of cast-iron repair must be carefully considered in the light of previous experience, and the best method decided upon only after all the aspects of the requirements of the finished weld have been decided. Preheating should be avoided wherever possible, and a great aid to this is the use of pure soft iron electrodes put on with thin runs. Experienced men can produce excellent results and guarantee an equal satisfaction to the original castings, but until such time as a non-destructive form of test can be applied to every weld, either as a visual X-ray shadowgraph or a magnetic indicator of serious discontinuity, there may always be a small proportion of cases in which disappointment occurs.—"Mechanical World and Engineering Record," March 6, 1931.

CREEP OF METALS AT ELEVATED TEMPERATURES.

By P. G. McVetty,[1] East Pittsburgh, Pa.

Flow Under Stress at Elevated Temperatures—Probable Nature of Creep Phenomena—Various Forms of Creep Curves—Metallurgical Aspects—Significance of Creep to the Designer of Parts to Withstand High Temperatures.

In the field of design today many important advances are waiting only for the development of reliable metals which may be depended upon to carry relatively high working stresses at temperatures from 750 degrees F. to 1200 degrees F. In many cases suitable materials are now available, but it

[1] M.E., Research Laboratories, Westinghouse Electric & Manufacturing Co. Mem. A.S.M.E.

Presented at the Western Metal Congress, San Francisco, Calif., February 16-21, 1931.

is necessary to choose the one best adapted to the particular application and to assign to it a safe working stress. The latter requires consideration of corrosion and erosion which may reduce the cross-section of metal carrying the load, and metallurgical changes within the material which may change its physical properties during its life in service. To these must be added a generous allowance for the unfortunate fact that alloy steels suitable for high-temperature applications have a tendency toward non-uniformity. As a result, the specimens tested may not truly represent the material in the section where stresses are maximum. If failure requires actual rupture of the metal, the problem is often simplified, but if the allowable deformation within the expected service life of the material is extremely small, it is usually necessary to depend upon some form of long-time tension test or "creep" test to establish safe working stresses.

DEFINITIONS OF CREEP.

In the past six or seven years the term "creep" has become quite familiar to all engineers. In its simplest form we may think of a vertical cylindrical rod supported at the top, carrying a constant load at the bottom, and heated to some constant high temperature over a definite portion of its length. If means are provided for measuring with great accuracy any change in length of the section in which stress and temperature are maintained constant, data may be obtained from which the usual creep curve can be plotted. Figure 1 shows some of the forms which this curve may have, depending upon the material, the temperature, and the stress. The several types of curves will be discussed later.

From a consideration of this simple case, we may define creep as the plastic deformation or permanent set which results from the continued application of stress at elevated temperatures. The deformation during the

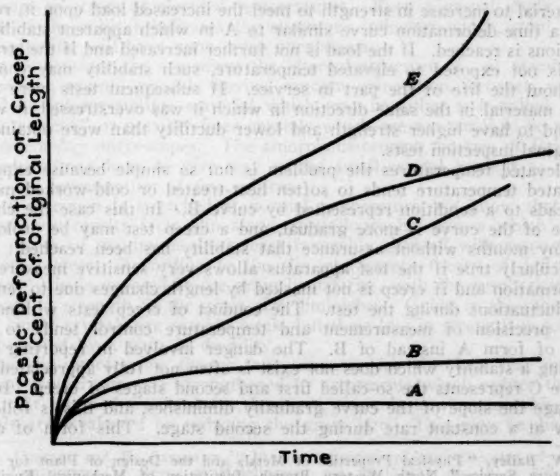

FIGURE 1.—VARIOUS FORMS OF CREEP CURVES.

application of the stress, which is usually a combination of elastic and plastic strain, is purposely excluded to simplify this discussion. The disadvantage of this definition is that it tells what creep *does* rather than what it *is*.

From the practical standpoint, creep tests must be limited in time, and much depends upon the extrapolation of curves to times equivalent to the expected life of the material in service. It is therefore of great importance to develop rational concepts of the fundamental nature of creep phenomena. It is extremely doubtful if a study of the deformation of a material under constant stress and temperature during a limited period of time is, in itself, a sound basis for predicting the deformation characteristics of the material up to the end of its life in service.

Returning to the thought of what creep actually is, we may quote a definition given by Bailey[2] which indicates that the problem is not simple. In Bailey's words: "Creep is the outward manifestation of the balance in the destruction of strain hardening by thermal influence and its recreation by further slip." On the surface this appears somewhat formidable, but it is essentially quite simple. It indicates primarily that creep is the net effect of two opposing forces, and this concept aids materially in the interpretation of the various forms of creep curves shown in Figure 1.

TYPICAL CREEP CURVES AND THEIR INTERPRETATION.

Curve A, Figure 1, represents a well-known case. During the readjustment of stresses in many structures, members may be temporarily overloaded, with the result that small plastic deformations occur. For example, this frequently happens during the construction of a bridge. If the amount of such deformation is small, no harm results. The deformation produces a small amount of cold work, which slightly increases the strength of the material and decreases its ductility. In some cases of overloading in service this deformation may be considerable. Within limits, the tendency is for the material to increase in strength to meet the increased load upon it, resulting in a time-deformation curve similar to A in which apparent stability of dimensions is reached. If the load is not further increased and if the strained metal is not exposed to elevated temperature, such stability may continue throughout the life of the part in service. If subsequent tests were made on this material in the same direction in which it was overstressed, it would be found to have higher strength and lower ductility than were obtained in the original inspection tests.

At elevated temperatures the problem is not so simple because exposure to elevated temperature tends to soften heat-treated or cold-worked metals. This leads to a condition represented by curve B. In this case the change of slope of the curve is more gradual, and a creep test may be prolonged for many months without assurance that stability has been reached. This is particularly true if the test apparatus allows very sensitive measurement of deformation and if creep is not masked by length changes due to temperature fluctuations during the test. The conduct of creep tests without the utmost precision of measurement and temperature control tends to give curves of form A instead of B. The danger involved in reporting tests indicating a stability which does not exist is often not fully appreciated.

Curve C represents the so-called first and second stages of creep. In the first stage the slope of the curve gradually diminishes, and this is followed by flow at a constant rate during the second stage. This form of curve

[2] R. W. Bailey, "Physical Properties of Metals and the Design of Plant for High-Temperature Service," North Western Branch, Institution of Mechanical Engineers, April 21, 1927. For abstract, see Engineering, vol. 124 (1927), p. 44.

has been used more than any other in published creep results, and much significance is placed upon the slope of the curve in the second stage or "creep rate." If we look upon creep as a net effect of strain hardening and annealing, this is seen to be a special case in which the relation between the two opposing forces remains constant over a long period of time.

Curve D is one frequently obtained in practice. It is like curve B in form, but the plastic deformation is greater. In spite of the gradually diminishing creep rate, it is usually conceded that stability will not be reached with this type of curve.

Curve E represents the condition of high stress or high temperature, or both. The stage of increasing creep rate or third stage usually begins with "necking" of the test specimen and ends in failure. The inflection in this curve is easily explained on the basis of stress changes. With a few exceptions, of which the work of Cournot and Sasagawa[3] is an example, all tensile creep tests in which the load is constant are assumed to have also a constant stress. As the test specimen extends, however, the cross-section diminishes and the unit stress increases. With relatively high stress or temperature or both, the total plastic deformation becomes large, and the error in assuming constant stress can no longer be ignored. When a creep curve shows this inflection, fracture is inevitable since the rate of flow increases to failure.

These curves indicate the value of Bailey's definition of creep. The various forms are easily explained by the concept of two opposing forces, one of which tends to decrease and the other to increase the creep rate.

METALLURGICAL SIGNIFICANCE OF CREEP PHENOMENA.

From the foregoing, it is evident that any prediction of the total creep within a time representing the service life of the metal requires a thorough understanding of the metallurgical changes which may result from long exposure to stress at elevated temperatures. Even a casual study of this phase of the subject indicates the enormous influence which grain growth and softening will have upon creep phenomena.

Let us consider for a moment the internal structure of our metals. The microscope reveals crystals having random orientation, between which is found an intercrystalline material which may be either a so-called "amorphous cement," or possibly finer crystals which are too small to be resolved by present-day microscopes. The amorphous-cement theories of Beilby and Rosenhain may have to give way to the small-crystal concept as a result of X-ray investigation of this subject.

If a specimen is stretched at normal temperature, we know that plastic deformation results from slip along crystallographic planes which coincide with planes of maximum shear least favorably situated with respect to the principal stress. According to the slip-interference theory of Jeffries and Archer,[4] slip is opposed at the grain boundaries, with the result that metals increase in strength as the grain size diminishes. Going in the other direction, single crystals are notably weak, but their loss in strength is somewhat compensated by a gain in ductility.

The slip-interference theory thus accounts for the fact that metals at normal temperature are strengthened by treatments which reduce the grain size. At elevated temperatures, however, there is now some evidence that metals are weakened by reducing the grain size. This may be due to the

[3] J. Cournot and K. Sasagawa, "The Investigation of the Viscosity of Alloys at High Temperature," Revue de Métallurgie, vol. 22 (1925), no. 12, p. 758.

[4] Z. Jeffries and R. S. Archer, "The Slip Interference Theory of the Hardening of Metals," Chemical & Metallurgical Engineering, June 15, 1921.

relative volume of material within and between the crystals. Carried to the extreme case, we should expect single crystals to have high resistance to creep. Experiments in this direction are now in process.

Regardless of the size of crystals, fracture at normal temperatures is generally intracrystalline. At high temperatures, on the other hand, we frequently find intercrystalline fractures. This leads to the idea of an "equicohesive" temperature at which the crystals and the material between them have the same strength. Theoretically, fracture will occur through the crystals themselves below this temperature, and between the crystals above this temperature.

In the present state of our knowledge, it is impossible to say whether creep is due to slip within the crystals, to plastic flow of the intercrystalline material, or to a combination of the two. Tests at normal temperature tend to support the first view, tests at very high temperatures the second, and a large number of intermediate tests appear to fall in the third class. Furthermore the location of the equicohesive temperature itself is uncertain, and appears to be very much influenced by the past history of the material. It is therefore quite possible that the laws which appear to govern creep phenomena during relatively short tests may change appreciably after long exposure to high temperature and stress. Since such changes are possible, great care must be used in the extrapolation of creep curves.

So far we have considered only the cold work due to creep itself, and the subsequent removal of this strain hardening by thermal influence. We may have in addition the effects of previous cold work such as rolling below the critical temperature or any other treatment which leaves internal stresses in the metal. In general, the greater the amount of cold work, the lower will be the temperature which will cause softening, or the shorter will be the time required to produce softening at a given temperature. The work of Pilling and Halliwell[5] and others throws considerable light on these phenomena.

Heat-treated materials also have a tendency to be unstable if subjected to long exposure to stress at elevated temperature. It is often claimed that a material which has been quenched and drawn may be exposed to any temperature below the drawing temperature for any length of time without further softening. Experiments show that this is not true, and the stability of heat-treated as well as cold-worked materials at high temperatures is open to considerable doubt. In many cases the time required is extremely long, but the study of thermal effects must give due consideration to the time of exposure to the high temperature.

Another metallurgical change which has a great influence on creep tests is the age hardening of certain alloys. This may not only reduce the creep rate to zero, but actually cause contraction of the test specimen. This phenomenon is due to precipitation of certain constituents, accompanied by increase in strength and decrease in ductility. However, the added strength from this change approaches a maximum, after which further exposure to elevated temperature results in a decrease of strength. Alloys in this class might easily show stability during a long period of test, after which creep would start and proceed at an increasing rate.

SIGNIFICANCE OF CREEP TO THE DESIGNER.

The designer may well say that he is not interested in all the metallurgical details which may influence creep. The answer is that the success or failure of his design may hinge upon the attention paid to these same details. It is

[5] N. B. Pilling and G. P. Halliwell, "Softening of Hard-Rolled Electrolytic Copper," Proc. A.S.T.M., vol. 25 (1925), part II, p. 97.

the duty of the designer to decide upon a safe working stress, and it has been shown that his choice must be based not only upon tests of the material involved but also upon a wide knowledge of materials under various service conditions.

In the early days of design it was sufficient to know the tensile strength of the material, and all other considerations were covered by a generous factor of safety. At that time the choice of materials was very limited, and service requirements were relatively easy to meet. As our knowledge increased and better materials became available, working stresses were raised to meet the demand for lighter, stronger parts. The element of cost cannot be ignored, and a more expensive material may be economically justified if it will carry a higher working stress. This again emphasizes the importance of a rational choice of working stresses.

When creep tests were first made, the idea prevailed that there was a determinable "creep limit stress" for a given material at any temperature. It was assumed that stresses above this limit would result in continuous plastic deformation, while below this limit stability of dimensions might be expected. To a certain extent this idea still exists, and we find a demand for creep limits which will yield safe working stresses upon application of a suitable factor of safety. Unfortunately, the bulk of experimental evidence indicates that real creep limits do not exist. The tendency is to design on the basis of maximum allowable deformation, and this requires the reliable determination of creep rates by carefully conducted tests. Since practical considerations limit the length of such tests, extrapolation of creep curves is necessary. It should be remembered, however, that many factors affect such extrapolation in addition to the length of straight edge available. It behooves the designer to adopt a critical attitude toward extravagant claims for the large number of alloys now on the market. It is quite possible that our greatest need is for more knowledge of present metals rather than for a marvelous material with properties exceeding our greatest expectations.

To a certain extent the designer is at the mercy of the metallurgist, as so much depends upon the treatment of the metal in making it ready for service. Also, the tendency toward non-uniformity previously mentioned is worthy of careful consideration by the producers of alloy steels. It sometimes happens that two test specimens which are supposedly identical show wide differences in properties. If more careful preparation of alloys can remove such conditions and the resultant uncertainty as to the accuracy of test results, it will be an accomplishment of real practical value.

CONCLUSIONS.

It is not the purpose of this paper to disparage any of the excellent testing work which has been and is being done. The author has been making long-time or creep tests for the past six years, and he fully appreciates the importance of such tests. It seems desirable, however, to bring home to mechanical engineers in general and to those engaged in design for high-temperature service in particular, the importance of a thorough knowledge of the action of various materials under the combined influence of stress, temperature, and time. The collection of reliable creep data for the numerous metals and alloys now available will require many years. In the meantime it is probable that extensive service applications will be made without having complete data on creep phenomena. These are, in themselves, the best kind of tests if accurate records are kept, and it is hoped that all such data will be carefully preserved and published. The extent of the problem is so great

and its importance so apparent that it merits the best efforts of mechanical and metallurgical engineers, and the close cooperation of those in the field with the most intimate knowledge of service conditions and performance.—"Mechanical Engineering," March, 1931.

THE HYDROGENATION OF PETROLEUM.

The Standard Oil Company's Statement.

By Mr. R. T. Haslam (Standard Oil Development Company) and Mr. R. P. Russell (Hydro Engineering and Chemical Company).

Some three years ago the Standard Oil Company (New Jersey), through its development company, joined with the I.G. in the further development and commercialization of hydrogenation, and erected special laboratories for high-pressure experimentation at the refinery of Jersey's subsidiary, the Standard Oil Company of Louisiana, at Baton Rouge, Louisiana.

Previous efforts had been largely directed towards the conversion of coal to gasoline or the conversion of asphaltic crudes and residual fuel oils to distillate naphthas and gas oils. Although work along these lines was continued with particular emphasis on the simplification of the process, much of the effort of the Baton Rouge staff, in co-operation with the I.G., was to broaden the use of the process. It is now felt that something more than a process of adding hydrogen to coal and oil has been developed, namely, a flexible method of treating and refining by the use of hydrogen of wide application in the oil industry.

In each of the major applications of hydrogenation, the equipment and even the arrangement are essentially the same, the results obtained being controlled by suitable alteration of operating conditions. The charging stock together with sufficient hydrogen is pumped into a reaction vessel containing catalyst, where at the desired temperature and at about 3000 pounds per square inch pressure the reaction is allowed to take place.

The oil and previously compressed hydrogen are mixed together and delivered through heat exchangers to a coil furnace and thence to a catalyst-containing reaction vessel. The degree of hydrogenation is carefully controlled, depending on the results desired, control in general being maintained either by alteration of catalyst or of operating conditions.

From the reaction chamber the combined final products and gases pass through heat exchangers and coolers to a high pressure separator, where the liquid product is separated from the unconsumed hydrogen and other gases. The liquid product is finally reduced to atmospheric pressure and sent to run-down pans. Much of the sulphur in the feed stock appears as hydrogen sulphide in the unconsumed hydrogen leaving the high-pressure separator. Since no coke is formed in the process, and since the catalysts employed are extremely rugged, the process is virtually continuous.

There are five adaptations of hydrogenation which appear to be of most immediate importance in oil refining. These are:—

(1) The conversion of heavy, high-sulphur, asphaltic crude oils and refinery residues into gasoline and distillates low in sulphur and free from asphalt, without concurrent formation of coke.

(2) The alteration of low-grade lubricating distillates, to obtain high yields of lubricating oils of premium quality as to temperature-viscosity relationship, Conradson carbon, flash and gravity.

(3) The conversion of off-color, inferior burning oil distillates or light gas oils into high gravity, low sulphur, water white burning oils of excellent burning characteristics, with gasoline being the only other product except for a slight gas formation.

(4) The desulphurization, color and gum-stabilization of high-sulphur, badly gumming cracked naphthas without marked alteration in distillation range and without major loss in anti-knock value. (It is possible to so operate as to actually better the anti-knock quality.)

(5) The conversion of paraffinic type gas oils into low sulphur, gum and color stable, good anti-knock gasolines without the production of coke or heavy product.

The processes described under (1), (2) and (3) above may all give more than 100 per cent volumetric yield; *i.e.*, from 100 barrels of a residual charging stock the process will give 101 or more barrels of gasoline and gas oil. Similarly, in treating 100 barrels of a low-grade lubricating distillate, 103 or more barrels of a mixture of gasoline and gas oil together with the improved lube oil will be obtained. In upgrading 100 barrels of a burning oil distillate, 102 or more barrels of product (approximately 70 per cent burning oil and 30 per cent gasoline) will be obtained.

The salient features of these adaptations of hydrogenation are discussed in the following sections.

The conversion of coal or heavy, asphaltic high-sulphur products into high yields of gasoline is probably the most widely discussed adaptation of hydrogenation. By the present methods of cracking, part of the charge stock is up-graded into light, valuable product in the form of gasoline, while the remainder is degraded into gas, coke, and heavy fuel oil, all of lesser value than the feed stock.

In contradistinction to the present processes for cracking, hydrogenation may up-grade even up to 100 per cent of the charging stock, into lighter and lower boiling point products. This major difference from the other forms of increasing gasoline yield, and the ability to utilize materials practically impossible to handle by other existing methods, tended to make this application of hydrogenation appear spectacular.

For the hydrogenation of heavy asphaltic crudes or residues from these crude oils or from cracking processes, two types of operation may be used. The first of these takes place mainly in the liquid phase and serves to convert the heavy charging stock into 100 per cent or more by volume of product of a more highly paraffinic nature than the charge-stock. The gasoline content may represent from 5 per cent to upwards of 35 per cent of the liquid product from this first stage in the operation and the balance is a distillate oil.

If a higher grade of gasoline is desired, the heavier part of the product may be recycled in the same unit or the total product may be hydrogenated in the vapor phase in a separate unit and converted completely to gasoline. During liquid phase hydrogenation, the asphalt content may be completely converted and two-thirds to three-fourths of all the sulphur in the charging stock eliminated.

The gas oil formed in the liquid phase operation, in addition to having a relatively low sulphur content, cracks to give a gasoline which finishes to specification easily even though the gas oil was produced by hydrogenating a high-sulphur, high-asphalt crude or residue.

In general it is felt that the early application of this phase of the hydrogenation process will be to run these heavy asphaltic products in the liquid phase to produce small yields of gasoline and the balance gas oil, with a total volumetric yield of 101 per cent to 104 per cent; the gas oil to be cracked to produce gasoline in existing cracking equipment or converted into good knock-rating naphtha by hydrogenation. If the gas oil is cracked in present apparatus, as much of the cracking plant tar as is needed for the production of steam and power in the refinery may be used as fuel and the balance returned to the hydrogenation unit.

Depending upon the stock and operating conditions, a yield of 80 per cent to 90 per cent of gasoline may be obtained by this method. If none of the cracking coil tar were burned as fuel, the combined yield of gasoline would be approximately 100 per cent.

Some typical examples of the liquid phase operation are given in the following table, in which a comparison is shown of the inspections of three heavy feed stocks before and after hydrogenation.

RESULTS OF HYDROGENATING HEAVY FEED STOCKS.

		Topped Crane Upton Crude		Topped Nacona Crude		Cracking Coil Tar	
Product—	Feed.	Product Ex. 1.	Product Ex 2.				
A.P.I. Gravity	23.4	35.8	35.1	24.9	37.5	12.4	23.5
I. B. P.	350	138	.....	344	130	340	153
Per cent at 212	.....	4.0	.....	.....	4.0	.....	3.0
Per cent at 284	.....	8.5	.....	.....	10.0	.....	6.5
Per cent at 374	.....	18.0	24.5	.....	21.0	.....	12.5
Per cent at 400	.....	22.0	30.0	1.0	25.0	0.5	14.0
Per cent at 460	6.5	33.5	41.0	1.5	36.5	.....	20.5
Per cent at 650	40.5	77.5	79.0	34.0	76.0	34.5	67.0
Per cent at 700	66.0	87.5	86.5	82.0	85.5	49.0	82.0
Per cent Sulphur	1.25	0.198	0.530	0.760	0.108	0.702	0.246
Per cent Gasoline*	.....	22.0	30.0	.....	25.0	.....	14.0
°A.P.I. Gasoline	.....	57.3	57.6	.....	60.8	.....	56.4
Per cent Sulphur in Gasoline	.....	0.034	0.056	.....	0.049	.....	0.019

A considerable amount of work has been done to determine whether by the use of the hydrogenation process all the requisite characteristics could be combined in a single lubricating oil. In general hydrogenated paraffinic lubricating oils with a flat temperature-viscosity relationship are characterized by unusually high flash points and low Conradson carbon content. The high quality of these hydrogenated lubricating oils predictable from the laboratory inspection has been substantiated in actual engine tests. In view of the possibility of producing essentially the same premium quality lubricating oils from a wide variety of inferior lubricating distillates, it would seem that hyrdogenation will have an important influence in this field of refining in the future.

It has been found that by hydrogenation it is possible to make marked improvement in a number of inferior quality lubricating distillates. Under the best conditions for this type of hydrogenation there is produced from 100 barrels of lubricating distillate 103 to 104 barrels of hydrogenated product containing from 60 to 85 barrels of lubricating oil, somewhat lower in viscosity but much more paraffinic than the charge, together with about 10 barrels of gasoline and from 10 to 30 barrels of gas oil. About 80—90 per cent of the sulphur in the feed stock is eliminated during hydrogenation.

High-sulphur, low-gravity, off-color kerosene distillates and poor quality light gas oils may be hydrogenated to produce high yields of water-white distillates and burning oils of high quality. In general these products meet specifications as to sulphur, color, and smoke tendency with no other treatment than reduction to flash and viscosity.

* Does not include a small yield of absorption naphtha produced concurrently.

In this adaptation of hydrogenation it has been found desirable to start with a stock somewhat more viscous than the desired finished oil, with the result that in many cases the actual yield of finished high grade burning oil has been greater than the amount of low grade material of kerosene boiling range and viscosity originally present in the charging stock. Liquid yields are from 100 per cent to 105 per cent by volume and the product from 65 per cent to 85 per cent of high-grade burning oil, the remainder being a gasoline.

All the hydrogenated burning oils have been found to be very stable. All the stocks, although different widely in initial chemical characteristics, after hydrogenation equal the very highest A.P.I. gravity natural burning oils in physical characteristics. Analysis indicates that by hydrogenation (a) olefines are almost completely eliminated; (b) the greater portion of the aromatics are converted into naphthenes and paraffins and (c) there is very little *apparent* effect on the naphthenes, probably since new naphthenes are formed from aromatics in the charge, thus off-setting the improvement brought about as the original naphthenes are changed into more paraffinic compounds.

In view of the remarkable facility with which catalytic hydrogenation eliminates sulphur, this process has been used for the treatment of natural or cracked naphthas. By a mild hydrogenation a high-sulphur, high-gum and unstable gasoline may be rendered stable, with about 50 per cent of the sulphur eliminated under such conditions of operation that the anti-knock value is lowered only to about the same extent as would result from a slight chemical treatment. This phase of the process would be carried out in such a way that no appreciable change would be made in the boiling range of the naphtha.

The process may also be so operated as to almost entirely eliminate sulphur from a high-sulphur, cracked naphtha, with a small increase and in some cases an actual decrease in knocking tendency. Depending upon conditions of operation, this treatment eliminates from 65 per cent to 98 per cent of the sulphur in the feed stock and gives a gum and color stable naphtha which, after a light wash with caustic soda, passes corrosion and doctor tests.

The production of stable low-knock gasolines by hydrogenation, although carried out in the same equipment as those modifications described earlier, differs from them considerably in both aims and results. For example, in converting a fuel oil into gasoline and gas oil, or in upgrading a lubricating oil or refined oil distillate, hydrogen is added to materials naturally deficient in this respect. In other words, hydrogenation has served to saturate the hydrocarbon molecule and render it more paraffinic.

By suitably changing the operating conditions, but still utilizing the same equipment, the process may be reversed to yield stable, but non-paraffinic products.

It will be recalled that in those adaptations of hydrogenation described earlier the volumetric yield is 100 per cent or more. This is not the case in producing gasoline from gas oil, unless the knocking tendency is immaterial, the yield of gasoline being less than 100 per cent if anti-knock quality is desired. In making anti-knock gasoline by hydrogenation, however, no tar or coke is formed and only two products are obtained, namely, gasoline and gas. Any material not converted into gasoline in the first pass through the system is recycled. The gasolines produced thus far have been practically sulphur-free, pass doctor and corrosion after lye-washing and are quite gum stable; in a few cases some treating has been necessary, but this has been very small in amount.

The following table shows quite strikingly this influence of character of charging stock on knocking tendency of the gasoline reduced:—

Gasoline Yield	89.9	91.4	88.0	89.0
Aniline Point of Charge Stock	161	139	102	79
General Characteristics of Charge	Highly Paraffinic	Medium Paraffinic	Medium Aromatic	Highly Aromatic
Knock Rating as per cent iso-octane in n-heptane	72.6	75.3	85.0	86.2

The potential value of these highly anti-knock gasolines as blending agents is readily apparent, and many interesting combinations with cracking have been developed by experimentation, *e.g.*, hydrogenation of cycle gas oils, to (a) increase gasoline yield; (b) decrease refinery fuel oil production, and (c) markedly better the knocking characteristics of the refineries' entire gasoline output.

The application of this phase of the hydrogenation process would appear to be wide, particularly as the need for low-sulphur, good knock-rating, stable gasoline becomes even more pronounced.

Consideration of the above illustrations leads to the following generalizations regarding hydrogenation:

(1) The type of hydrogenation employed in treating petroleum oils differs materially in all the major aspects from hydrogenation of the Sabatier type in that (a) hydrogen at high pressure is used; (b) the hydrogen is relatively impure and contains hydrogen sulphide; (c) the catalysts are sulphur resistant, and (d) relatively higher temperatures are employed.

(2) Long-time runs of 6 to 8 months on commercial apparatus at high temperature may be made without coke or tar formation. The 90 per cent point or the final boiling point of the product throughout the run may be less than that of the charging stock.

(3) Sulphur, an ever-mounting problem in the oil industry, is readily eliminated. This holds true for all the forms of sulphur formed in a wide variety of crudes. In a recent vapor phase operation on a unit producing over 2500 barrels of product per day the sulphur content was reduced from 0.708 per cent to under 0.01 per cent, or an elimination of over 98.5 per cent. In general it may be said that when operating in liquid phase the elimination will be 60 per cent to 75 per cent and in vapor phase from 80 per cent to 99 per cent.

(4) Asphaltic residues of all sorts from reduced natural crudes to cracking coal tar can be converted to distillate products free from asphalt and low in sulphur with volumetric yields in excess of 100 per cent. The hydrogenation process, therefore, offers the oil industry (a) a means of confining its production of heavy fuel to its economic market demand, and (b) a means of balancing crude production against the demand for refined white products, gasoline, Diesel fuels, burning oils and the like, independent of the natural, heavy fuel content of the crude.

(5) From mixed base crudes, highly paraffinic products such as gas oils, burning oils and lubricants may be produced. On the other hand, from paraffinic crudes so-called aromatic products may be formed, as for example a highly anti-knock gasoline from a very paraffinic gas oil. Even from the same gas oil paraffinic burning oil and anti-knock gasoline may be made. Consequently from any given supply of crude the products of the quality desired may be produced by refineries employing hydrogenation.

(6) The flexibility of the process is very marked as to character of the charging stock and quality of product produced. The same plant may be used (a) for producing gasoline and gas oil; (b) very paraffinic high A.P.I. gravity burning oils from mixed base gas oils; (c) color and gum stabilizing and desulphurizing highly cracked naphthas; (d) production of paraffinic lubricants from mixed base stocks, and (e) production of anti-knock, high compression gasoline from paraffinic gas oils. Further, from the above examples it may be seen that from *practically any grade of crude oil products of any desired quality may be produced.*

(7) The hydrogenation process uses compressed hydrogen, a rather costly material. Offsetting this are the following factors: (a) the ability to balance crude run to white product demand; (b) the premium quality of products produced; (c) the low value charging stocks that may be used, and (d) the extreme utility of the process, due to its flexibility, especially where types of crudes to be refined and markets to be supplied vary from time to time.

(8) Because of the over supply of crude oil, hydrogenation in its present state of development may be considered as supplementary to present refining methods. It probably will supplant them as the supply of crude oil and demand for light products approach a balance.—"The Petroleum Times," March 21, 1931.

BOOK REVIEWS.

I MOTORI MARINI A COMBUSTIONE INTERNA (Marine Internal Combustion Engines) By Benvenuto Rossi. 396 Pages, 277 Illustrations, Published by Stabilimento Tipografico Trinchera Co., Via Pietro Giannone 77-83, Napoli.

The author, who is Engineer-Colonel of the Italian Navy and founder of the Italian magazine "Rivista Marine e Tecnica Nautica," prepared this book as one of a series of books for the instruction of the engineer officers of the Italian Navy. The book is largely descriptive in character and has a wealth of technical material in it, covering all the well known types of Diesel engines. The first few chapters are devoted to thermodynamical considerations and a brief historical sketch of the original experiments carried out by Diesel, after which follow descriptions of typical examples of the main parts of the mechanism of the engine, such as cylinders and heads, pistons, framing, etc. The remaining chapters describe most of the principal designs of engines with their distinctive features and with brief historical reviews of their development. Many excellent cuts of large scale drawings serve to illustrate the subject matter; these were selected with great care and deserve much praise for the author.

The book, however, although it is claimed to be used for the instruction of naval personnel, has no drawings and makes no reference to Diesel engines used for the propulsion of naval vessels, such as submarines for instance, which are now universally propelled by this type of engine. Only a brief historical sketch covering the war-time development of the well known 12,000 S.H.P. M.A.N. engine intended for battleships is included. It would also appear that the recent development of supercharging, which is of primary importance for all marine purposes and particularly for the navies of the world—it having been recently applied to a submarine propelling plant—would make supercharging deserving

of a chapter in the book. All present development tends to point to the rapid adoption of high speed types of Diesel engines not only for naval propelling plants, such as those in the German cruisers *Königsberg* class, *Leipzig* and *Ersatz Preussen*, but even for more general application in merchant ships and these bring with them the problems of balancing and torsional vibration, which ought to have found some space in a book of this kind. Nevertheless, the above remarks need not be construed as detracting from the value of what can be found in the book by any engineer even with only a rudimentary knowledge of the Italian language.

E. C. MAGDEBURGER.

PRINCIPLES OF ENGINEERING THERMODYNAMICS. By PAUL J. KIEFER, A.B., M.E., PROFESSOR OF MECHANICAL ENGINEERING, U. S. NAVAL POSTGRADUATE SCHOOL, AND MILTON C. STUART, M.E., PROFESSOR OF EXPERIMENTAL MECHANICAL ENGINEERING, LEHIGH UNIVERSITY. PUBLISHED BY JOHN WILEY & SONS, INC., NEW YORK CITY; 1930.

In this interesting work on the basic theory underlying engineering the authors have aimed "to conform with the trend in engineering education toward an increasing emphasis upon the fundamental sciences . . ."

The book is divided into five parts:

Part I.—The First Law of Thermodynamics.

Part II.—The Second Law of Thermodynamics and the Carnot Principle.

Part III.—The Physical Properties of Vapors, Gases and Their Mixtures.

Part IV.—Analyses of Motive-Power Machinery and Power Using Apparatus, Taking up Ideal Performances and Departures Therefrom.

Part V.—General Thermodynamic Equations for Use in Further Applications in Physics and Chemistry.

There are included in the text representative problems and at the end of each chapter a summary of the important features thereof, together with questions which are of great help to the student.

Older engineers who desire to review their engineering thermodynamics and put themselves in a position to use with confidence as a reference book a modern text, and all engineers interested in establishing their knowledge of this subject on more solid ground, will find much stimulating food for thought presented in an understandable manner.

Engineers attacking problems outside of the old well beaten tracks and finding that their methods do not give consistent results should be very much interested in the methods based on fundamentals which are indicated for the solution of these problems.

H. F. D. DAVIS.

MODERN DIESEL ENGINE PRACTICE. By ORVILLE ADAMS. THE NORMAN W. HENLEY PUBLISHING CO., NEW YORK, N. Y. PRICE $6.00, NET.

This book of nearly 600 pages was written to assist in the sale, purchase, installation, erection, operation, and upkeep of the Diesel engine.

The *Salesman* will here find a wealth of data to assist him in selling; the *Buyer* will learn how to select the engine and its auxiliaries; the *Installation Man* and *Erector* will find valuable chapters on "Engineering the Diesel Plant," and the *Operator* can find many useful facts and hints on the operation and repair of his Diesel plant.

The book is admittedly not intended as a guide to the designer or constructor of Diesel engines.

Advertising is unavoidable in works of this nature which are so largely dependent upon the cooperation of commercial firms for the data and information. However, this book contains less propaganda than is customarily to be found in similar publications.

The adequate indexing and careful arrangement of "Modern Diesel Engine Practice" recommend it as a well written reference book for the practical information needed by those concerned in the handling of the Diesel engine after it leaves the shops of the manufacturer.

JOHN O. HUSE.

ASSOCIATION NOTES.

The annual banquet of the Society was held at Washington, D. C,. on February 19, 1931. It proved one of the most successful and enjoyable of these events, from every standpoint, ever held by the Society.

Rear Admiral H. E. Yarnell, U. S. N., President, welcomed the guests and Rear Admiral W. D. Leahy, U. S. N., acted as Toastmaster. The speakers were Honorable Charles Francis Adams, Secretary of the Navy, Rear Admiral F. B. Upham, U. S. N., Chief of the Bureau of Navigation, and Mr. James L. Ackerson, Director of the Bureau of Construction, United States Shipping Board.

Through the courtesy of the Chesapeake and Potomac Telephone Company two very interesting and instructive motion pictures illustrative of the development of sound moving pictures from the basic principles of the telephone were shown. A musical program was rendered by an orchestra of the United States Band.

The committee in charge comprised Captain I. E. Bass, U. S. N., Captain O. L. Cox, U. S. N., Captain S. C. Hooper, U. S. N., Commander Bryson Bruce, U. S. N., and Mr. B. P. Lamberton.

The Society regrets very much to announce that Rear Admiral H. E. Yarnell, Chief of the Bureau of Engineering and President of the Society, and Rear Admiral John Halligan, Assistant Chief of Naval Operations, and Captain Ivan E. Bass, of the Council, are being detached from duty in Washington.

MEMBERSHIP.

The following members have joined the Society since the publication of the last previous JOURNAL:

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